LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
LUT School of Energy Systems
Degree Programme in Nuclear Energy Engineering

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Analysis of VVER-1200 Passive Heat Removal Systems: Steam Generator PHRS and Containment PHRS

Examiners: Professor Juhani Hyvärinen

Supervisors: Dr. Juhani Vihavainen

ABSTRACT

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Master's Thesis

May 30, 2019

56 pages, 39 figures, 11 tables and 2 appendices
Examiners: Professor Juhani Hyvärinen
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Keywords: thermal hydraulics, passive systems, VVER-1200, passive heat removal system, PHRS, ATHLET, nuclear power

Passive safety systems used in nuclear power plants were examined in this thesis. First these systems have been introduced. Phenomena related to these systems were explained. Model systems were shown.

This work focuses on the analysis of passive safety systems that uses natural circulation. These systems enable circulation of coolant by means of natural circulation for cooling of the nuclear reactor in case of accident.

Purpose of this thesis is to shown it is beneficial to model natural circulation analytically by comparing analytical model with computer model created by nuclear system code. In addition to that is the test the performance of passive heat removal systems.

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. Juhani Vihavainen for his endless support and Professor Juhani Hyvärinen for helping me with his most valuable knowledge about the concepts of natural circulation.

It was a great opportunity to have the experience of study in Finland. I would like to thank all of my friends whom accompanied me during that time.

May, 2019

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LIST OF SYMBOLS AND ABBREVIATIONS

Roman alphabet

A	area	m^2
D	diameter	m
f	friction factor	-
g	gravitational acceleration	m^2/s
G	mass flux	kg/m^2s
h	enthalpy	kg/ms^2
H	distance	m
K	loss coefficient	-
L	length	m
p	pressure	Pa, bar
P	pressure	Pa, bar
q_m	mass flow	kg/s
Q	heat	W
x	vapor mass quality	-
T	temperature	°C

Greek

α	void fraction	-
Δ	difference	-
μ	viscosity	kg/m.s
ρ	density	kg/m^3
σ	surface tension	N/m
Φ	Two-phase multiplier	-

Subscripts

a	acceleration
c	cold
CL	cold leg
d	density
f	friction, fluid

g	gravity, gas
h	hot, hydraulic
HE	heat exchanger
HL	hot leg
hom	homogenous
l	liquid
lo	liquid only
SG	steam generator
TP	two-phase
v	vapor
vo	vapor only

Abbreviations

ATHLET	Analysis of Thermalhydraulics of Leaks and Transients
BDBA	Beyond Design Basis Accident
BWR	Boiling Water Reactor
CHF	Critical Heat Flux
CANDU	CANada Deuterium Uranium
ECCS	Emergency Core Cooling System
EUR	European Utilities Requirements
FEBE	Forward Euler, Backward Euler
HX	Heat Exchanger
IAEA	International Atomic Energy Agency
I&C	Instrumentation and Control
IC	Isolation Condenser
ITF	Integral Test Facility
LBLOCA	Large Break LOCA
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
MCP	Main Coolant Pump
NPP	Nuclear Power Plant
PHRS	Passive Heat Removal System
PRHR	Passive Residual Heat Removal

PWR	Pressurized Water Reactor
RBMK	Reaktor Bolshoy Moshchnosti Kanalniy
RCS	Reactor Coolant System
RPV	Reactor Pressure Vessel
SBLOCA	Small Break LOCA
SBO	Station Blackout
SG	Steam Generator
VVER	VodoVodjanyi Energetitseskij Reaktor

1. INTRODUCTION

Nuclear power generation covers the 10.4% of the world electricity consumption. The sector constantly tries to improve safety of the Nuclear Power Plants. Trends show that nuclear power generation will still be an important element in electricity generation.There are 450 nuclear power reactors exits as of year 2017 and 60 are under construction(World Nuclear Association, 2019).

New designs have better safety and operational performances compared to older ones. That improvement mostly resulted from the past accidents. In Fukushima accident long term cooling of the reactor core could not achieved because of the power loss in pumps. Passive safety systems work without pumps and do notneed electrical supply. A nuclear reactor produces large amount of heat even after shutdown. This residual heat should be transferred to heat sink for cooling the reactor core. Depending on their capacity, a passive core cooling system can cool the reactor core for a long period of time, whichcan prevent the core meltdown and respectively release of radioactive materials to the public.

After Fukushima accident most of the countries implemented additional safety measures to their NPPs. Some countries such as Russia and China established passive safety systems to their plant design for a prolonged cooling (Lee *et al.*, 2017)

Russian type pressurized water reactor VVER-1200/AES-2006 power plant designed with passive safety systems to increase its safety performance. Steam generator passive residual heat cooling system and containment passive heat removal system are two passive systems tobe used in long time cooling at severe accidents. These systems rely on natural circulation for cooling, which can be modeledanalytically. Cooling performance of these passive safety systems in VVER-1200 has been studied with system code ATHLET and an analytical calculation method.

1.1 Thesis Purpose

Objective of this thesis is to assess the efficiency of an analytical model to analyze the flow loops, which can be used to model a national circulation in a reactor system. For that purpose, an analytical model was constructed with using momentum equation throughout the system in question. Two of VVER-1200 passive safety system relies on natural circulation for their operation. One of that provides passive heat removal from steam generator and the other one provides containment cooling by passive means of heat removal.

Using analytical expressions for the analysiseliminates the necessity of system code models; thus gives an opinion about the system performance in a fast manner. Downside is the model can be lack of precision. Another advantage of an analytical model is that; even if an analytical model is not enough to test the system performance, it provides data in preparing the computer model input.

In order to test the natural circulation model performance, systems were also modeled with system code ATHLET. ATHLET code has been validated by various experiments and the development of the code continues by adding new capabilities.

2. VVER 1200/AES-2006 NUCLEAR POWER PLANT

The latest design of VVER reactor is VVER1200 – AES 2006. AES 2006 is a Gen III+ type NPP. VVER-1200/AES-2006 has two different versions. Moscow Atomenergypro designed the V-392M version, which is based on AES-92 design, and St. Petersburg Atomenergypro designed the V-491 version, which is based on AES-91 (Rosatom, 2015). Major differences between two designs are; (IAEA, 2011)

- Steam generator passive residual heat removal and containment passive heat removal systems in V-491
- Passive core flooding system in V-392M
- V-491' active systems for high and low pressure emergency injections
- Systems against beyond design basis accidents
- Core damage frequencies
- I&C System, the feed water system, main control room layout
- NPP layout

2.1 VVER-1200/AES-2006 V-491

VVER-1200/V-491 design was created by St. Petersburg Atomenergypro with scientific support from Kurchatov Institute. Russian regulatory documents, IAEA safety requirements and European Utilities Requirements (EUR) were fulfilled in the design (IAEA, 2011). Simplified schematic diagram of the power plant is shown in figure 2. Basic specifications of the plant are shown in table 1.

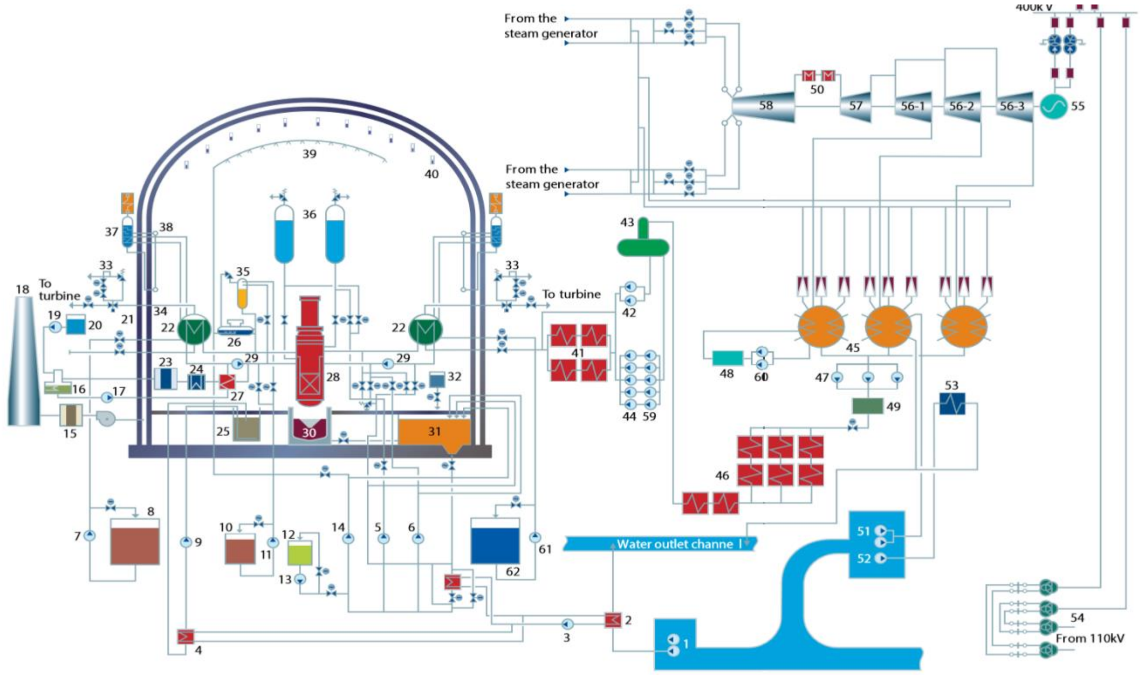

Figure 1: VVER-1200/V-491 Schematic diagram

1)Service water pump; 2) intermediate cooling circuit heat exchangers; 3) intermediate circuit pump; 4) spent fuel pool heat exchanger; 5)ECCS, low pressure pump; 6)ECCS, high pressure pump; 7) emergency feed water pump; 8) storage tanks for high boric acid concentration; 9) spent fuel cooling pump; 10) storage tanks for boric acid solution; 11) emergency boration system pump; 12) storage tank for chemical reagents; 13) supply pump for chemical reagents; 14) containment spray system pump; 15) filter; 16) volume and chemical control system deaerator; 17) volume and chemical control system pump; 18) ventilation stack; 19) controlled-leak pump; 20) controlled-leak tank; 21) external containment; 22) steam generator; 23) water treatment facility; 24) after-cooler; 25) spent fuel pool; 26) bubbler tank; 27) regenerative heat exchanger for the volume and chemical control system; 28) reactor; 29) reactor coolant pump; 30) core catcher; 31) emergency core cooling system sump and add water storage tank; 32)emergency tank for NaOH reserve; 33) MSIV, safety and relief valve assembly; 34) containment; 35)pressurizer; 36) ECCS hydroaccumulators; 37) passive heat removal system tank; 38) condenser for the containment passive heat removal system; 39) spray system; 40) passive hydrogen protection system; 41) high-pressure heaters; 42) auxiliary feed water pump; 43) deaerator; 44) electric-powered feed water pump; 45) condenser; 46) low-pressure heaters; 47) condensate pumps, first stage; 48) de-mineralized water unit; 49) main condensate treatment; 50) super-heater; 51) circulation cooling water pumps; 52) cooling water pump for turbine hall demands; 53) turbine hall consumers; 54) stand-by step-down transformer; 55) generator; 56) low-pressure turbinesections; 57)intermediate pressure turbine sections.; 58)high-pressure turbine; 59) boost pump; 60) condensate pumps for de-mineralizationunit; 61) emergency feed water pump; 62) demineralized water storage tank (Rosatom, 2015).

Table 1. Characteristics of VVER-1200/V-491 (Givnipet, 2014).

General Parameters	
Rated thermal power of reactor, MW	3200
Rated electric power, MW	1198,8
Effective hours of rated power use, hour/year	8065
Primary Circuit	
Number of loops	4
Coolant flow through the reactor, m^3/h	85600±2900
Coolant temperature at reactor inlet/outlet, ^oC	298.6/329.7
Pressure, MPa	16.2
Secondary Circuit	
Pressure, MPa	7.0
Feedwater temperature, ^oC	225±5

2.2 VVER-1200 Primary Components

2.2.1 Reactor Pressure Vessel

Reactor vessel covers the core, in-core instrumentation system parts and control rod mechanism. Vessel material faces a high neutron flux from the core. In VVER-1200 vessel is designed to withstand 60 years of operation lifetime with a neutron flux of $4.22 \cdot 10^{19}$ neutron/cm^2/s. Detailed drawing of the reactor is show in Figure 2(Rosatom, 2015).

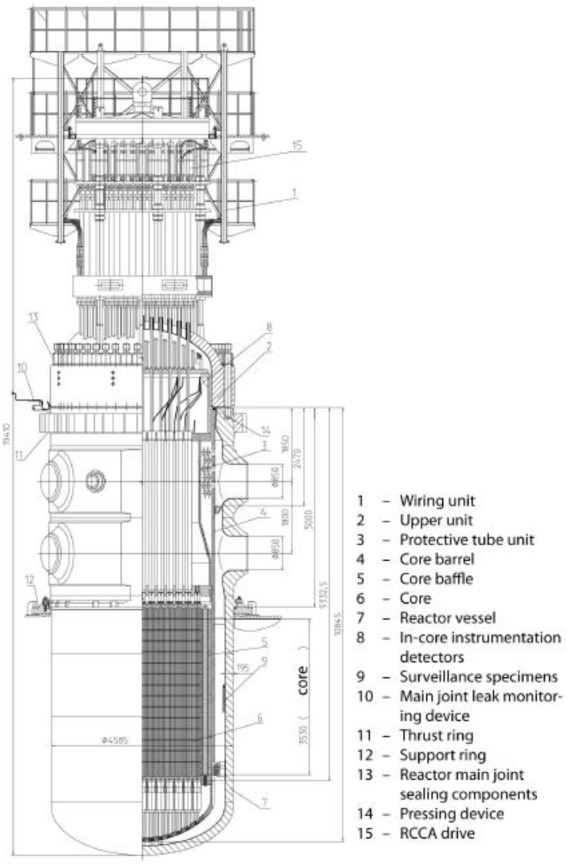

Figure 2: Pressure vessel of VVER-1200 (IAEA, 2011).

2.2.2 Steam Generator

The steam generators used in VVER-1200 are PGV-1000MKP type horizontal steam generators. Steam generator produces saturated steam for the turbines and cools the primary circuit coolant. Heat transfer provided by the U-type tubes fixed in the tube bundle. Performance of the steam generator is given at Table 2.

Table 2: Performance parameters of **PGV-1000MKP** (V.V. Parygin, 2012)

Thermal Power [MW]	803
Capacity [kg/s]	445
Outlet steam temperature [°C]	285.8
Steam Pressure [MPa]	7
Feed water temperature [°C]	225
Device length [m]	14.75
Body diameter [m]	4.49

2.2.3 Main Coolant Pump

Reactor coolant pump (RCP) circulates coolant in the primary circuit of the reactor plant. RCP is a vertical centrifugal pump with a capacity of 21500 m^3/h at 17.64 MPa design pressure (IAEA, 2011).

2.3 Safety Concept

V-491 safety systems designed according to single failure, redundancy, diversity, physical separation, and inherent safety criteria (IAEA, 2011). AES-2006 uses active and passive safety systems. Two sets of these safety systems are shown inTable 3.

Table 3: Active and Passive Safety features at VVER-1200/V-491 (IAEA, 2011).

Active Systems	Passive Systems
• High pressure emergency spray system • Low pressure emergency spray system • Emergency gas removal system • Emergency boron injection system • Emergency feedwater system • Residual heat removal system • Main steamline isolation system	• Emergency core cooling system, passive part • Steam generator passive residual heat removal system • Containment passive heat removal system • Double containment • Core catcher

2.3.1 Passive Safety Systems

Loss of offsite power simultaneous with a turbine trip and unavailable standby AC power systems has been considered as a credible event after Fukushima Daiichi accident. IAEA has recommended implementing passive systems to new NPP designs in order to prevent station blackout accidents (SBO) mitigation to the severe accident with core damage(IAEA, 2015).

Passive systems should provide decay heat cooling for at least 72 hours after SBO or failure of ECCS in loss of coolant accident (LOCA). These systems consist of low-pressure water tanks of ECCS, and system for removing heat from steam generator and containment (Aminov and Egorov, 2017).

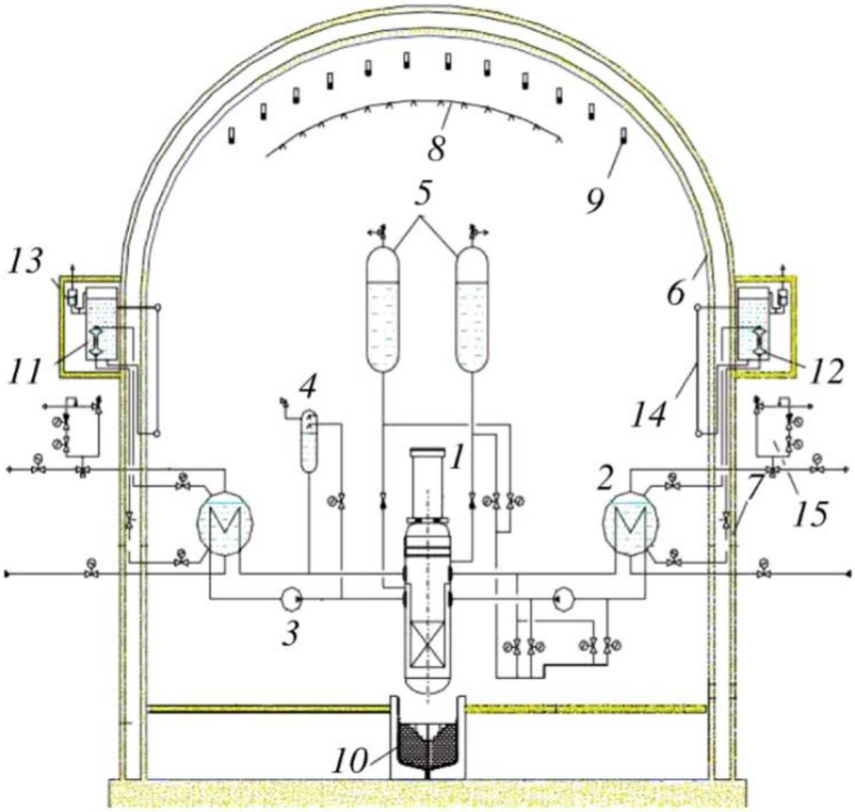

Figure 3: Passive systems configuration inV-491 design

1) reactor; 2) steam generator; 3) MCP; 4) pressurizer; 5) tanks of the emergency core cooling system; 6) inner containment shell; 7) outer containment shell; 8) sprinkler manifold; 9) passive hydrogen re-combiner; 10) core catcher; 11) emergency heat removal tank of the passive heat removal system; 12) heat exchanger of the passive heat removal system; 13) hydro-valve; 14) condenser-heat exchanger of the passive heat removal system from the containment shell; 15) main steam reinforcement block (Aminov and Egorov, 2017).

Tanks of emergency core cooling system (ECCS) provideboric acid solution supply during a severe accident with loss of coolant(IAEA, 2011). That system relies on gravity to inject water to the reactor core.Steam generator passive heat removal system (SG PHRS)designed for removing residual heat during accident conditions such as loss of offsite power and loss of primary circuit integrity (Asmolov *et al.,* 2017). SG PHRS operates with natural circulation in both of its circuits (Bakhmet'ev *et al.,* 2009).

Containment passive heat removal system (Containment PHRS) prevents the overpressurization inside the containment in BDBA(Rosatom, 2015). Containment PHRS condenses the steam inside the containment by natural circulation in its closed loop (Bezlepkin *et al.,* 2014). Double containment and core catcher contains the radioactivity released in a severe accident and limits the radiation exposure (IAEA, 2011).

Containment PHRS and SG PHRS are the two critical systems that both relies on natural circulation in their closed loops. These two systems use the same pool with pipe sections implemented near each other as can be seen from Figure 4.

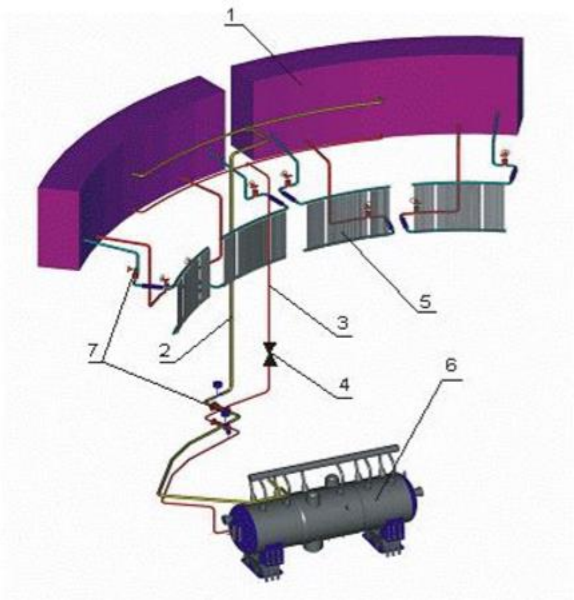

Figure 4: Containment and SG PHRS

1) Emergency heat removal tanks, 2) Steam lines, 3) Condensate pipelines, 4)SG PHRS valves, 5)Heat exchangers of Containment PHRS, 6) Steam generator, 7) Cutoff valves (Givnipet, 2014)

2.3.1.1 Containment Passive Heat Removal System

Containment PHRS contains four modules with same heat transfer capacity. Operation of three modules is sufficient for system to function. Each module consists of four heat exchangers that are connected to the heat sink water tank. Location of heat exchangers inside the containment is shown inFigure 5.

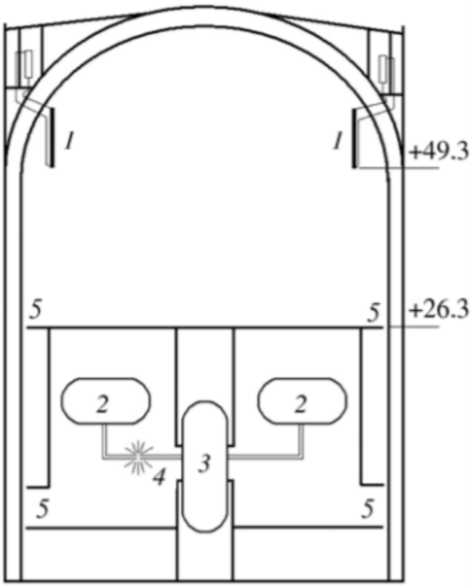

Figure 5: Containment PHRS operation

1) Heat exchanger; 2) steam generator; 3) reactor; 4) rupture; 5) steam gas mixture (Bezlepkin *et al.*, 2014).

Steam discharges into containment from ruptured pipeline, rises to the heat exchanger. It condensates on the surface of the heat exchangers and heat is transferred to the water in the Containment PHRS module. Consequently, natural circulation arises from the density change of the heated coolant at heat exchanger and heat is transferred to water tanks between the two envelopes of double containment and from there to the atmosphere (Bezlepkin *et al.*, 2014).

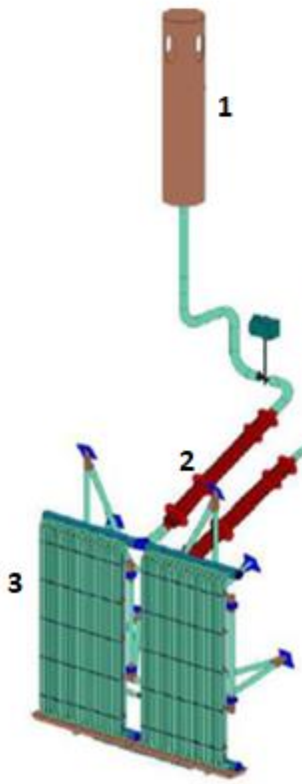

Figure 6: Single module of Containment PHRS.
1: PHRS tank, 2: pipelines, 3: heat exchanger surface (Rosatom, 2015).

Containment PHRS designed to remove heat from containment for more than 24 hours. It is a passive safety measure for BDBA (Givnipet, 2014). Containment PHRS functions can be listed as (Rosatom, 2015);

- Prevents the overpressurization inside the containment in BDBA
- Transfers the heat released into containment to the heat sink
- Act as a substitute for the spray system

2.3.1.2 Steam Generator Passive Heat Removal System (PHRS)

SG PHRS designed to remove the heat from the core by secondary circuit in the event of unanticipated accident such as loss of electrical power or feedwater, or leak in the primary circuit. For heat sink, SG PHRS uses water tanks that are open to the atmosphere. There is a tubular heat exchanger inside the water tanks. Steam extracted from steam generator condenses inside the heat exchanger and returns back to steam generator. V-491 water-cooled heat exchangers have better heat transfer efficiency than V-392M air-cooled heat exchangers. As water at atmospheric pressure in the tanks evaporates, it extracts more energy from steam inside the heat exchanger. That provides fast cooling with a compact system, and gives enough response time for filling the water tanks(Kukhtevich *et al.,* 2010).

SG PHRS can cool down the reactor for 72 hours hence it requires at least 3 of 4 primary circuits stay intact to function properly since it designed to have diversity with 4x33% capacity.The tanks of SG PHRS also can be used for flooding of the core in case of loss of coolant at primary circuit (Aminov and Egorov, 2017).

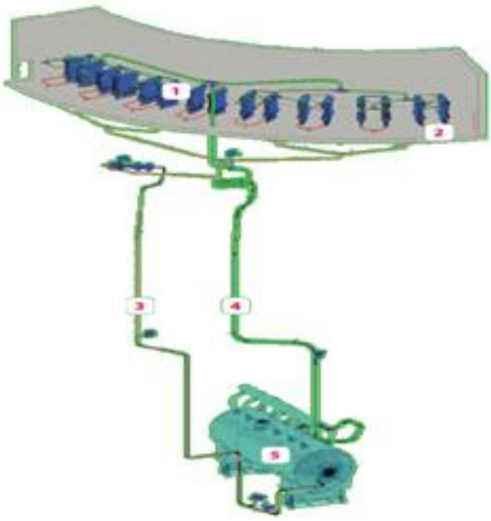

Figure 7: Containment and SG PHRS

1) Emergency heat removal tanks, 2) Heat exchangers, 3) Return pipe, 4)SG PHRS outlet pipe, 5) Steam generator(Rosatom, 2015).

SG PHRS functions can be listed as (Rosatom, 2015):

- Residual heat removal and shutdown cooling in case of loss of offsite power
- Residual heat removal and shutdown cooling in absence of feed water supply
- Prevention of radioactivity release from steam bypass or SG safety valves in the event of leakage from primary or secondary circuit
- Reduction of radioactivity when primary coolant leaks to secondary circuit at the same time steam pipeline rupture occursbefore pipeline isolation valve outside the containment

3. PASSIVE SAFETY SYSTEMS IN WATER COOLED NUCLEAR POWER PLANTS

Passive systems acting as accumulators, condensations, evaporative heat exchangers, and gravity driven safety injection systems can be used in place of active systems that uses pumps, generators and other type of electrical power supplies, which enhances a cost in installation, maintenance and operation of these systems. Therefore, passive systems were started to be often used in new generation reactors. In addition to reduced cost, passive safety systems provides better safety with better system reliability(IAEA, 2009).

3.1 Passive Safety Systems for Decay Heat Removal

In order to remove decay heat after reactor scram, various passive safety systems are being used in NPPs. These systems are listed as;

3.1.1 Pre-pressurized Accumulator Tank

Accumulator tanks or flooding tanks are used in emergency coolant system. 75% of the tank is filled with borated water and the rest of the volume is filled nitrogen or inert gas to pressurize the tank. Check valves prevent borated water injection to the reactor coolant system (RCS) during normal operation.When the pressure in the RCS drops to accumulator tank pressure level in case of LOCA, these valves open and borated water releases to the reactor pressure vessel (IAEA, 2009).

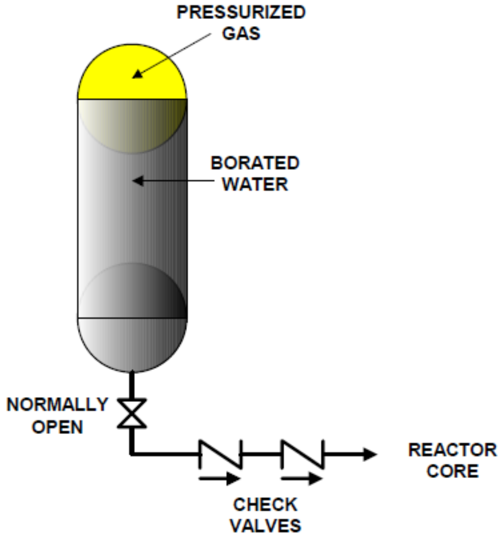

Figure 8: Pre-pressurized accumulator tank (IAEA, 2009).

3.1.2 Elevated Tank Natural Circulation Loops (Core Make-up Tanks)

Tanks filled with borated water are connected to the reactor coolant system from the top of the tank andthe valves in that pipe section are normally open. Tanks are isolated with valves at pipes that are connected from the bottom of the tank, goes to reactor pressure vessel (Figure 9).In case of emergency bottom valve is opened, thus cold coolant enters to RPV then water accumulates in the system by natural circulation (IAEA, 2009).

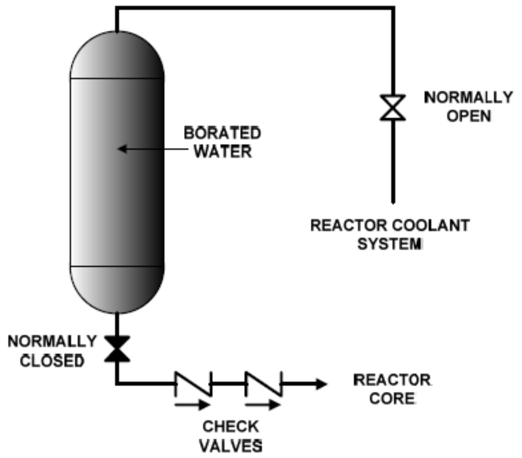

Figure 9: Core make-up tank (IAEA, 2009).

3.1.3 Passively Cooled Steam Generator Natural Circulation

In this systems decay heat can be removed via steam generators. Steam discharged from steam generators condenses in the heat exchangers located inside a large pool (Figure 10) or in an air cooling tower (Figure 11), then cooled (IAEA, 2009).

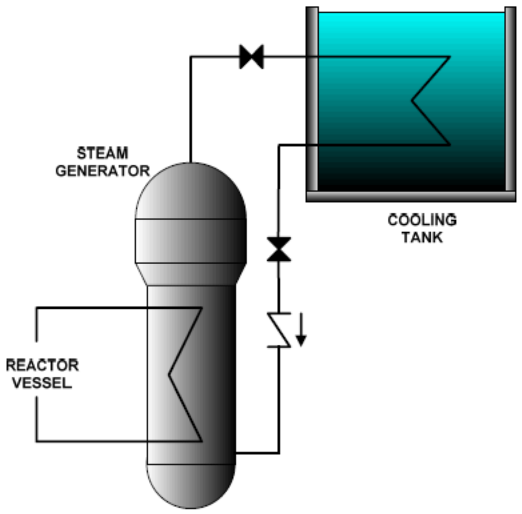

Figure 10: Heat removal using passively cooled steam generator (water) (IAEA, 2009).

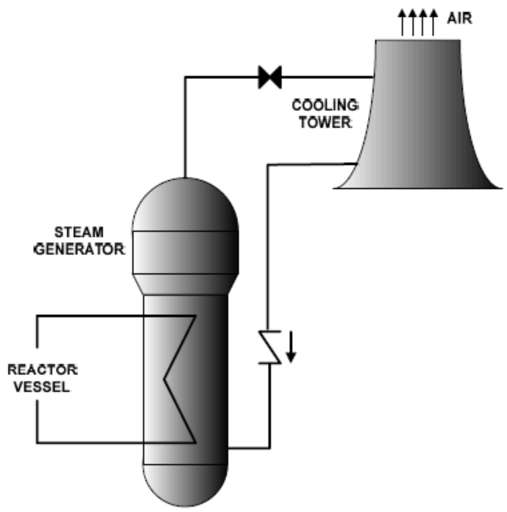

Figure 11: Heat removal using passively cooled steam generator (air) (IAEA, 2009).

3.1.4 Passive Residual Heat Removal Heat Exchangers

Passive residual heat removal (PRHR) system provides core cooling by natural circulation for an extended time. Single-phase liquid heat transfer is used in this system. Schematic of the system is shown in Figure 12(IAEA, 2009).

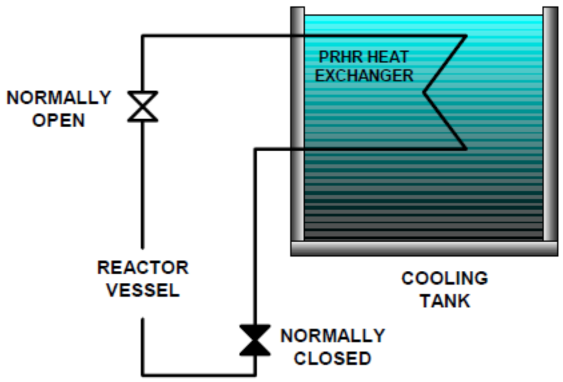

Figure 12: Core decay heat removal using PRHR heat exchanger loop (IAEA, 2009).

3.1.5 Passively Cooled Core Isolation Condensers (steam)

Passively cooled core isolation condensers (IC) is used in BWRs for core cooling when the primary means of cooling is insufficient. ICs are normally isolated from the reactor vessel; valves are opened in case of emergency. Steam extracted from reactor vessel condenses in heat exchangers inside the pools then returns to the reactor vessel. Steam circulates passively by natural circulation (IAEA, 2009).

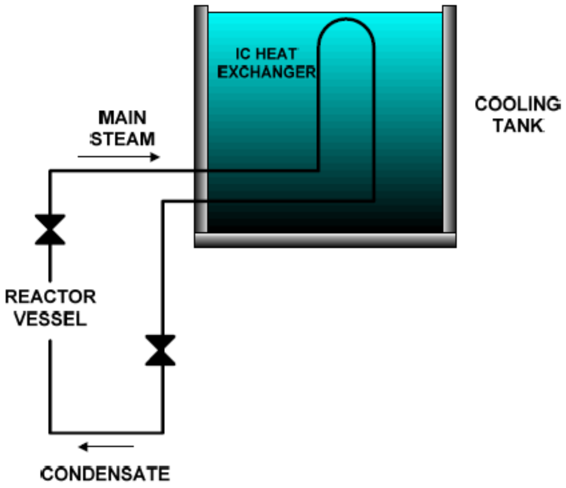

Figure 13: Isolation condenser cooling system (IAEA, 2009).

3.2 Passive Safety Systems for Containment Cooling and Pressure Suppression

Steam discharges to containment during loss of coolant accident increasing the pressure in the containment. Thus,several systems have been designed to cool the containment and reduce the containment pressure.

3.2.1 Containment Pressure Suppression Pools

Containment pressure suppression pools have been used in BWRs for some time. In an event of LOCA steam discharges to drywell, then diverted to the suppression pools from vent lines as shown in Figure 14. Then steam condenses in suppression pools and preventingthe pressure increase inside the containment (IAEA, 2009).

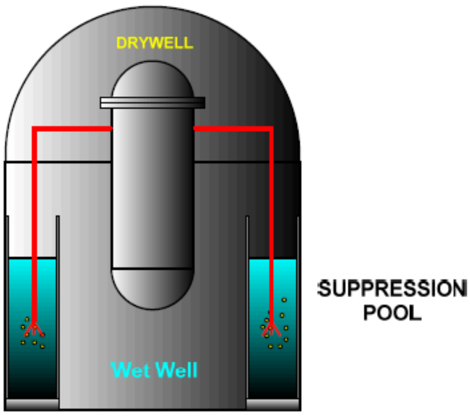

Figure 14: Containment pressure reduction after LOCA using suppression pool (IAEA, 2009).

3.2.2 Containment Passive Heat Removal/Pressure Suppression Systems

In these systems, steam released inside the containment building condenses on the surfaces of the heat exchanger tubes. There are two different versions of these systems, both uses elevated pools as a heat sink. In first version as seen in Figure 15; air type heat exchanger connected to the pool at the top of containment. Single-phase liquid circulates in the system by natural circulation (IAEA, 2009).

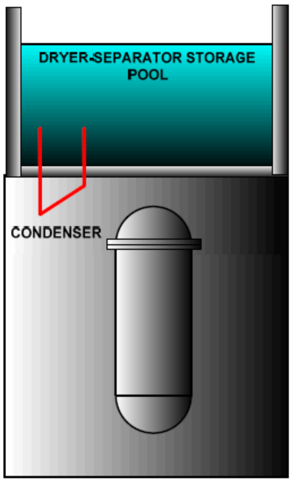

Figure 15: Containment cooling with steam condensation on condenser tubes (IAEA, 2009).

In the second version, shown in Figure 16; again steam inside the containment condenses on the tube surfaces of the air type heat exchanger inside the containment, therefore a pool-type heat exchanger implemented inside the heat sink. Workingfluid circulates with the density differences caused by heating at containment and cooling inside the pool (IAEA, 2009).

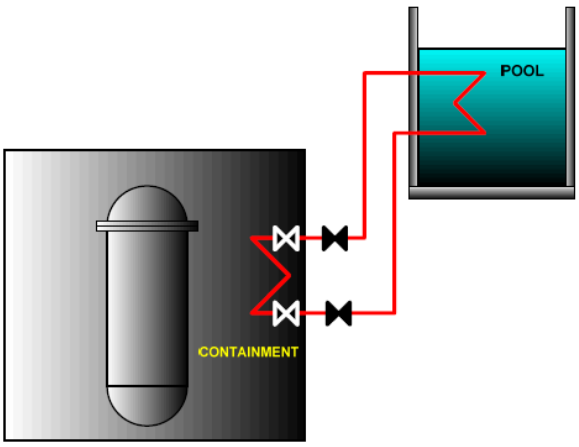

Figure 16: Containment cooling with external natural circulation loop (IAEA, 2009).

4. NATURAL CIRCULATION IN A CLOSED LOOP

Natural circulation in a closed loop occurs in a loop with a heat sink placed at higher elevation than the heat source (Figure 17)

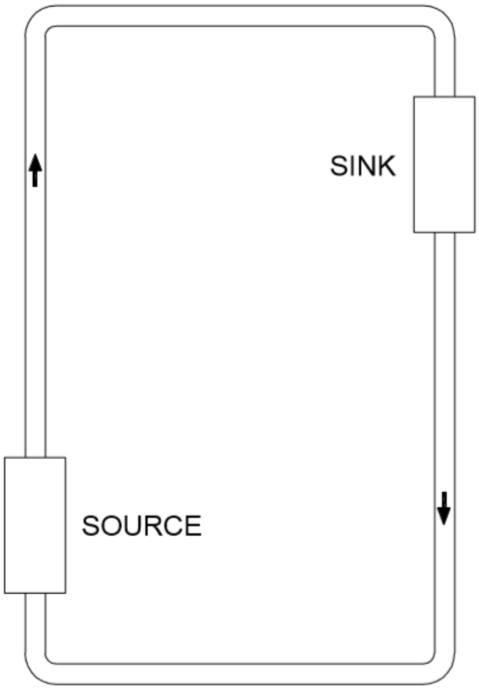

Figure 17: Scheme of natural circulation loop.

Fluid in loop heated by the heat source, density of the heated fluid in contact with the heat source decreases, fluid exits on the heat sink section of the loop loses energy from heat sink and its density increases. That difference in densities when combined by gravity and the elevation difference establishes a buoyancy force, which circulates fluid in the loop. This circulation is called as natural circulation (IAEA.,2005).

Density difference caused by the heat transfer can be resulted from change in temperature or the phase of the fluid. Friction in the loop restrains the fluid flow in the loop. Natural circulation flow rate increases with the difference between hot and cold leg densities and decreases with the pressure losses in the loop. The balance equation (1)can be written as;

$$\Delta P_d = \Delta P_f + \Delta P_l + \Delta P_a \quad \textbf{(1)}$$

$\Delta P_d$is the pressure change from the density change along the loop as shown in equation (2).

$$\Delta P_d = \oint \rho dz \quad \textbf{(2)}$$

Single and two-phase density and single and two phase pressure loss components are the main parameters for determining the natural circulation flow rate.

Along with the flow rate,other variables should be considered in natural circulation loop. Figure 18 shows the phenomena that can occur in the loop, in the heat source and in the sink.

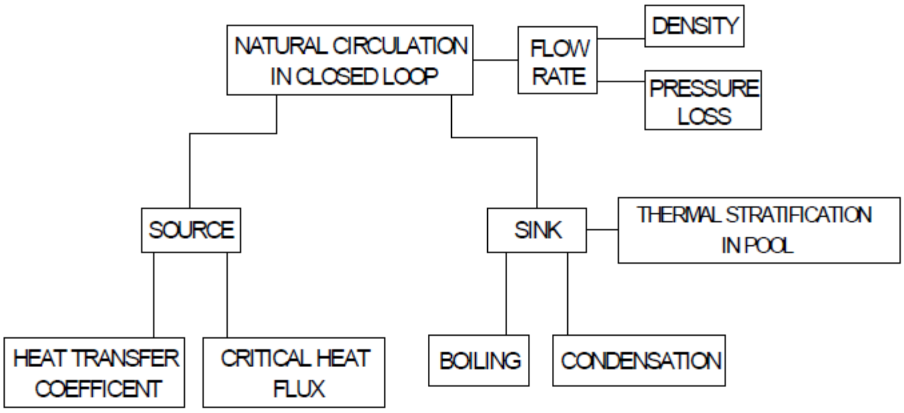

Figure 18: Phenomena in natural circulation in closed loop (IAEA,2005).

In nuclear systems depending on the natural circulation circuit, heat source can be reactor core or steam generator primary side. Nevertheless, heat transfer from surface of the source to the coolant occurs with the heat transfer coefficient. Critical heat flux is the maximum heat flux reached in the heat source, dry out or departure from nucleate boiling (DNB) occurs if CHF reached.

In Pressurized Water Reactors (PWR), steam generator is used as a heat sink for transferring primary coolant heat to the coolant in secondary coolant circuit. That heat initiates boiling in secondary circuit. Steam produced in steam generator condenses after being used in turbines. In Boiling Water Reactors (BWR), primary coolant boils in the reactor core;therefore, primary coolant used in turbines and condenses in condensers.

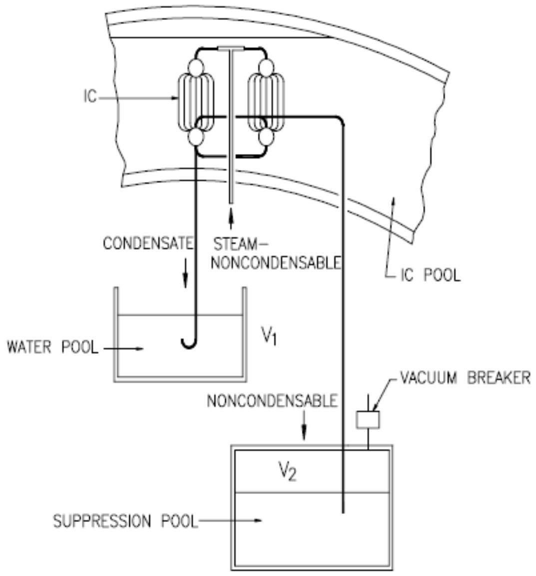

Figure 19: Isolation Condenser (IC) system(AGENCY, 2005).

Water pools can be used as a heat sink to remove decay heat or heat released in containment (Figure 19). Thermal stratification can occur in the water pool, which greatly affects the heat transfer at heat exchangers inside the pool(IAEA,2005).

In today's NPPs natural circulation mainly used for inherently core decay heat removal in accident situations. In next generation power plants, it will be considered as a normal means of core cooling and planning to have a more capabilities in accident situations (IAEA, 2015).

Use of natural circulation in normal operating and abnormal conditions is summarized in Table 4. In normal operating conditions, natural circulation occurs at steam generator operation and startup and shutdown of BWR plants. In abnormal conditions small break LOCA (SBLOCA) and the last phase of LBLOCA should be considered(IAEA, 2015).

Table 4. Relevant natural circulation scenarios(IAEA, 2015).

	Reference Condition			
	Normal		Abnormal	
Reference System	1 Φ	2 Φ	LBLOCA (end phase)	SBLOCA, MCP, trip
BWR & RBMK		X	X	X
SG (secondary side)		X		X
PWR, VVER, CANDU	X		X	

Natural circulation in PWRs establishes if the density differences in the primary loop is large enough to overcome friction losses from loop components. Density difference results from heating in the core section and cooling in the steam generators. This mechanism helps to remove decay heat from the core. Natural circulation cooling can be separated into three modes, which are; as shown in Figure 20; single and two-phase natural circulation and reflux condensation. When the amount of liquid in the loop starts to decrease,single-phase natural circulation becomes two-phase and if it continuous to decrease eventually reflux mode occurs (IAEA, 2015).

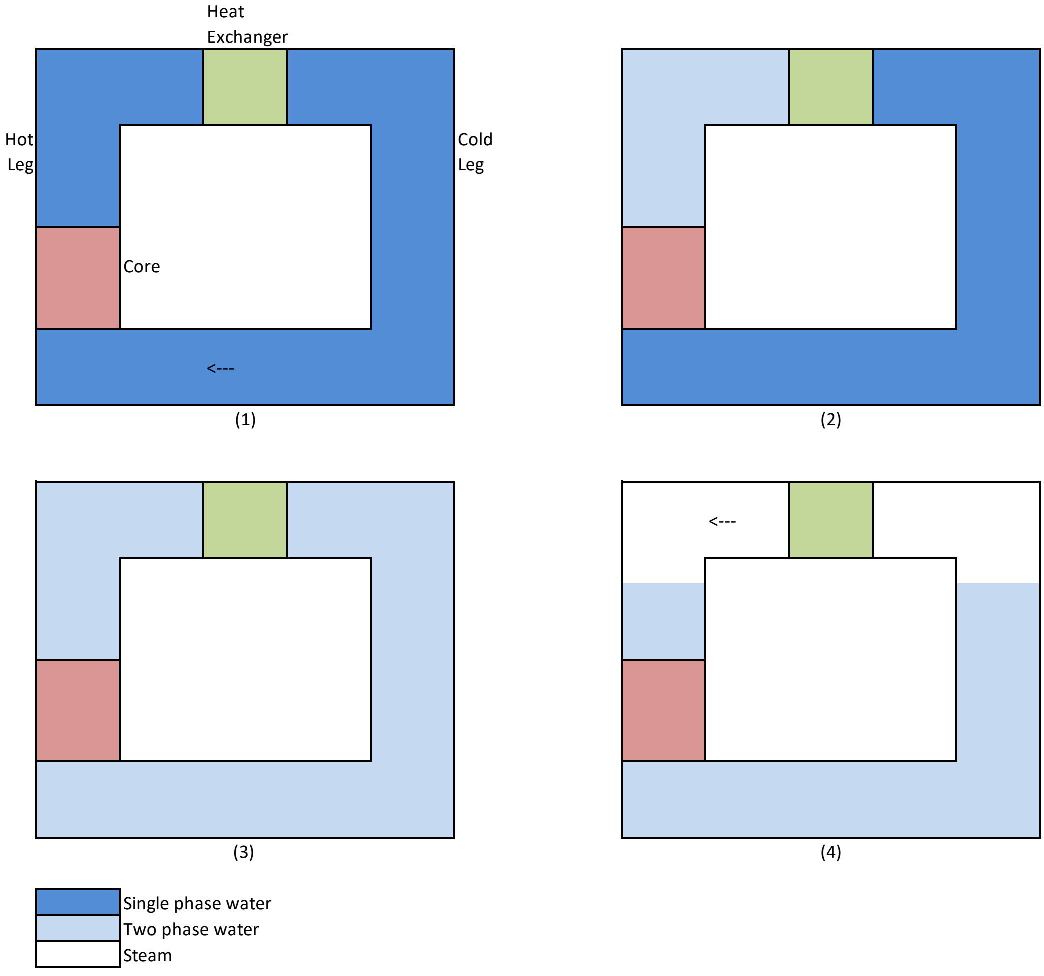

Figure 20: Different modes of natural circulation.

1) Single-phase circulation 2) Two-phase natural circulation in hot leg 3) Two-phase circulation 4) Reflux condensation (IAEA, 2015).

In single-phase natural circulation sub-cooled water circulates in the loop. Thus,two-phase natural circulation is defined as steady circulation of water and vapor mixture in the loop.

Water starts to boil in the core region and becomes mixture of vapor and saturated water.When vapor reaches the steam generator some of it condenses, therefore the density difference between hot and cold leg generated from voids in the loop, not from temperature differences. Heat removal effectiveness is directly related to mass flow rates in both single- and two-phase circulations. In reflux condensation, vapor condenses in the steam generator and turns into liquid then returns back to the core. Rather than loop mass flow rate, condensation rate is important in that mode (IAEA, 2015).

4.1 Natural Circulation Modeling

Thermalhydraulic analysis of the reactor system in normal and abnormal conditions can be done by computer codes that are created for that purpose or test facilities that are constructed to mimic transitions in real nuclear power plants(IAEA, 2002).

4.1.1 Natural Circulation Experiments

Integral test facilities (ITFs) were used in designing and safety assessment stages of nuclear reactors. Results of ITFs tests give a valuable data for benchmarking of the computer codes for nuclear safety. ITF has similar thermalhydraulic characteristicsof a nuclear power plant but it is scaled down from reactor system of interestto reduce cost of a full scale test.

These test can also be assess a certain phenomenon at the reactor system. Natural circulation phenomenon has been studied in various test facilities. It is possible to imitate a NPP response in case of an accident in ITF that are designed for that certain facility and to examine predetermined phenomenon.

Natural circulation mode in PWRs changes according to heat source and mass inventory of the loop. These modes were previously listed in Figure 20. Each mode corresponds a different flow pattern for natural circulation and various tests were conducted in ITFs to examine the natural circulation flow patterns.

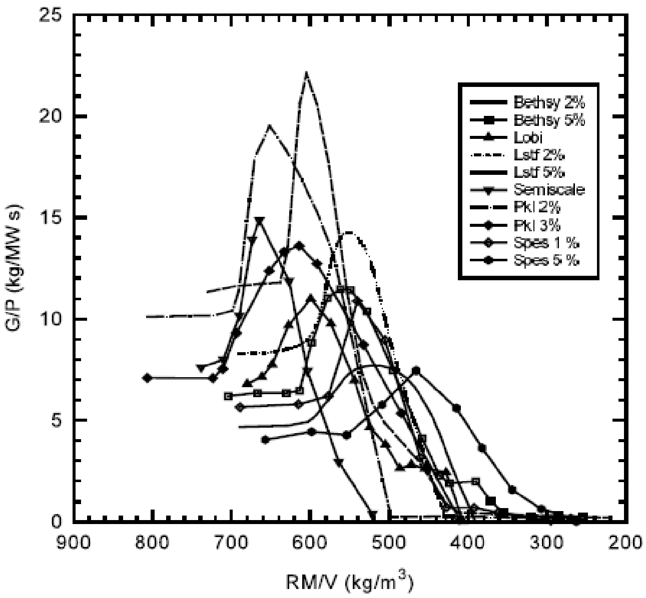

Figure 21: Natural Circulation flow regime composed from ten experiments in six ITFs (D'Auria, Francesco and Frogheri, 2002).

Figure 21 shows the natural circulation flow behavior with respect to coolant inventory change. G is core inlet flowrate (kgs^{-1}), core power is P (MW), primary system mass inventory is RM (kg) and the constant volume of the primary system is V (m^3). Natural circulation experiments performed with decreasing the system mass inventory and PWR heat power decay simulated (D'Auria, Francesco and Frogheri, 2002). Properties of these six ITFs can be seen at Table 5.

Table 5: ITFs characteristics used in natural circulation experiments (D'Auria, Francesco and Frogheri, 2002).

Item	Semiscale Mod2A	Lobi Mod2	Spes	PKL-III	Bethsy	LSTF
Reference reactor and Power (MW)	W-PWR 3411	W-PWR 2775	KWU-PWR 3900	FRA-PWR 2775	W-PWR 3423	
Number of fuel rods simulators	25	64	97	340	428	1064
Number of U-tubes per SG	2/6	8/24	13/13/13	30/30/60	34/34/34	141/141
Internal diameter of U-tubes (mm)	19.7	19.6	15/4	10.0	19.7	19.6
Actual Kv	1/1957	1/589	1/611	1/159	1/132	1/48

Natural circulation regimes are identified in Figure 22. Change from single-phase through reflux condensation mode occurs with decrease in mass inventory.

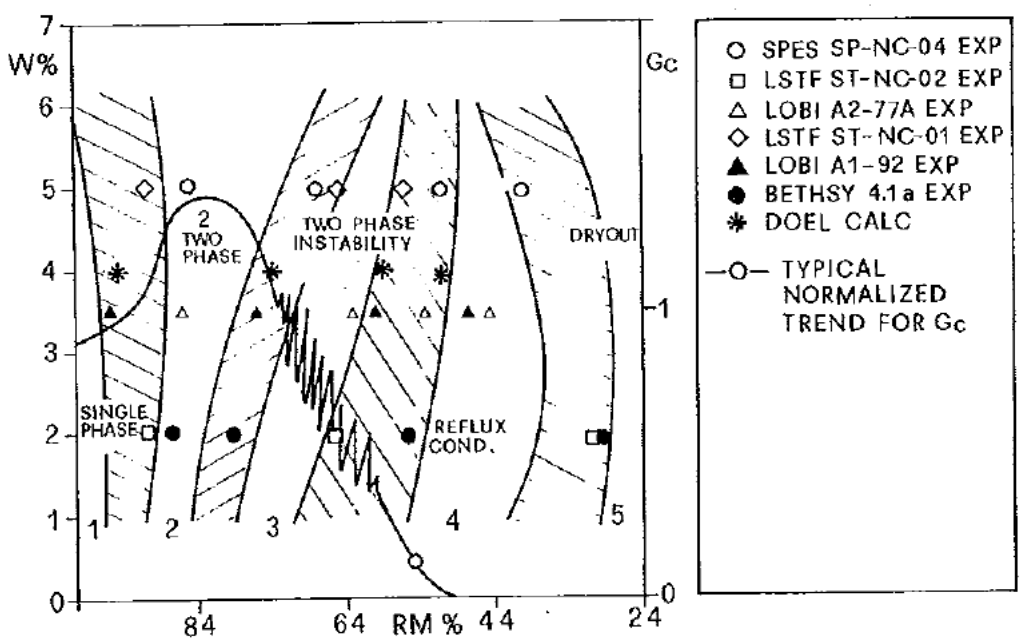

Figure 22: Flow regimes occurred in natural circulation with change in mass inventory (D'Auria, F. *et al.*, 1991).

4.1.2 Computer Modeling

Reactor system can be simply modeled with analytical models if certain assumptions were made in the system or modeling can be extended to complex system codes, which contain numerical solutions of partial differential equations in three-dimensionalspacein transient conditionsto model natural circulation in reactor systems. APROS, ATHLET, CATHARE and TRACE are widely used system codes for thermalhydraulic analysis. Each of them solves the main governing six partial differential equations(IAEA, 2002).

Since these system codes contain numerical approximations and empirical models, they have been constantly validated starting from their first development. The validations have been done at least by experiments at test facilities. In addition, real plant data has been used in the validations.

Thermalhydraulic system code enables numerical definition of the plant. Fluid stream tubes and solid components that store heat or heat sources are treated within certain boundary conditions and assumptions. Sections of the plant are divided into nodes (control volumes) according to their thermalhydraulic properties. The model is constructed by nodalization of plant components (D'Auria, Francesco *et al.,* 2006).

5. TEST FACILITIES FOR PASSIVE HEAT REMOVAL SYSTEMS OF VVER-1200

In this section test facilities that were designed for experimental studies of thermalhydraulic performances of AES-2006 reactor passive safety systems were introduced. GE2M-PG test rig in Leypunsk Institute for Physics and Power Engineering is used for the analysis of steam generator. Large scale KMS stand on the site provides experimental analysis of passive cooling of the containment.

5.1 GE2M-PG Test Rig

In GE2M-PG test rig the reactor is cooled by evaporation of coolant in case of decay heat removal with SG PHRS. Some part of generated steam enters to steam generator and returns to core after condensation. Removed power from steam generator at condensation mode depends on the temperature difference between circulating reactor coolant and the coolant at the shell section, consecutively the difference between coolant at secondary section of steam generator and the PHRS service water at V-491 or outside air temperature at V-392M (Morozov and Remizov, 2012).

When steam generator switches to condensation mode, heat flux in the steam generator becomes much smallerthan the normal operation. Studies of heat exchanger operation at low heat fluxes was very limited, therefore GE2M-PG test rig was constructed (Morozov and Remizov, 2012).

Test rig has one 1:48 scaled down VVER steam generator, 16 m^3 accumulator tank and PHRS with service water cooling. Flow diagram of the test rig can be seen inFigure 23. In the GE2M-PG test rig effect of non-condensable gas concentration and steam gas mixture flow at the header of the steam generator were analyzed for examination of the performance of the PHRS (Morozov *et al.*, 2017).

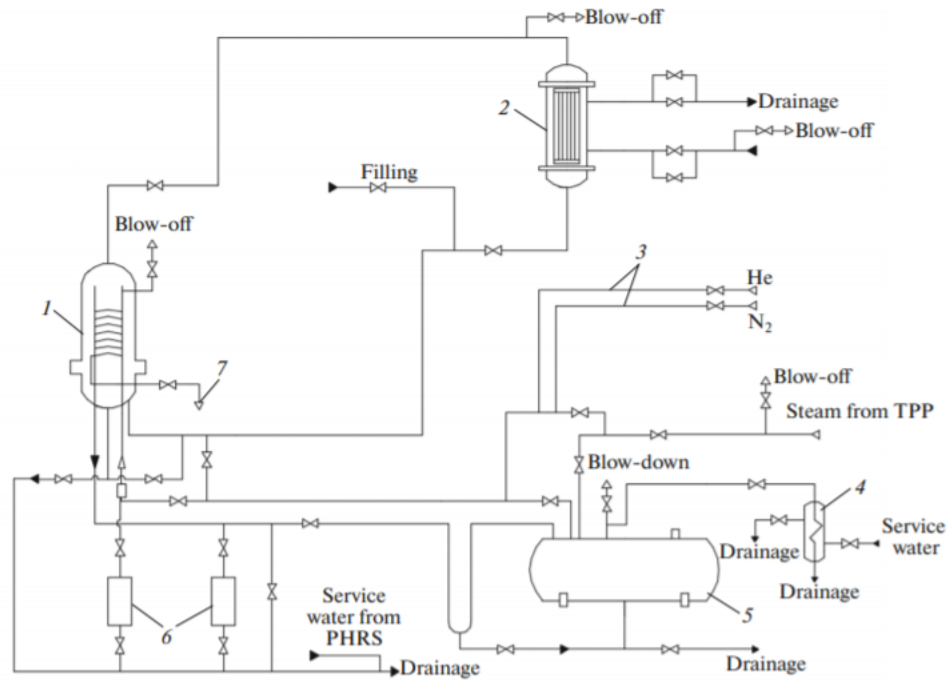

Figure 23: GE2M-PG test rig diagram.

1) Steam generator; 2) Heat exchanger of PHRS; 3) Non-condensable gas feed; 4) Pressurizer; 5) Steam accumulator; 6) Condensed water tank; 7) Steam-gas removal (Morozov *et al.*, 2017).

5.2 KMS Test Facility

KMS-1 consists of a containment vessel, vessel room, containment passive heat removal system, spent fuel cooling system and spray system. Volumetric scaling factor of the containment for VVER-1200 reactor is 1:27.

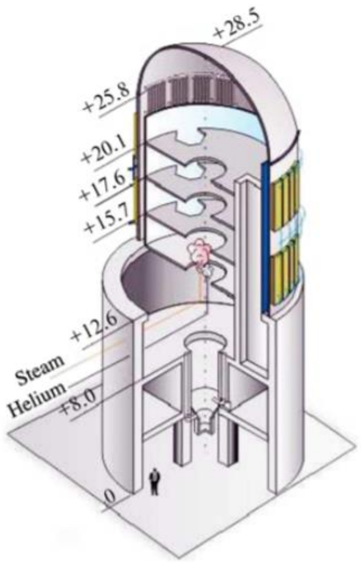

Figure 24: KMS Containment(Vasilenko *et al.*, 2014).

In order to test containment PHRS performance, heat exchangers were implemented around the containment under the dome section. Heat exchanger surface temperatures, containment temperatures, thermalhydraulic properties of steam-gas mixture and condensation inside the containment can be measured in KMS.

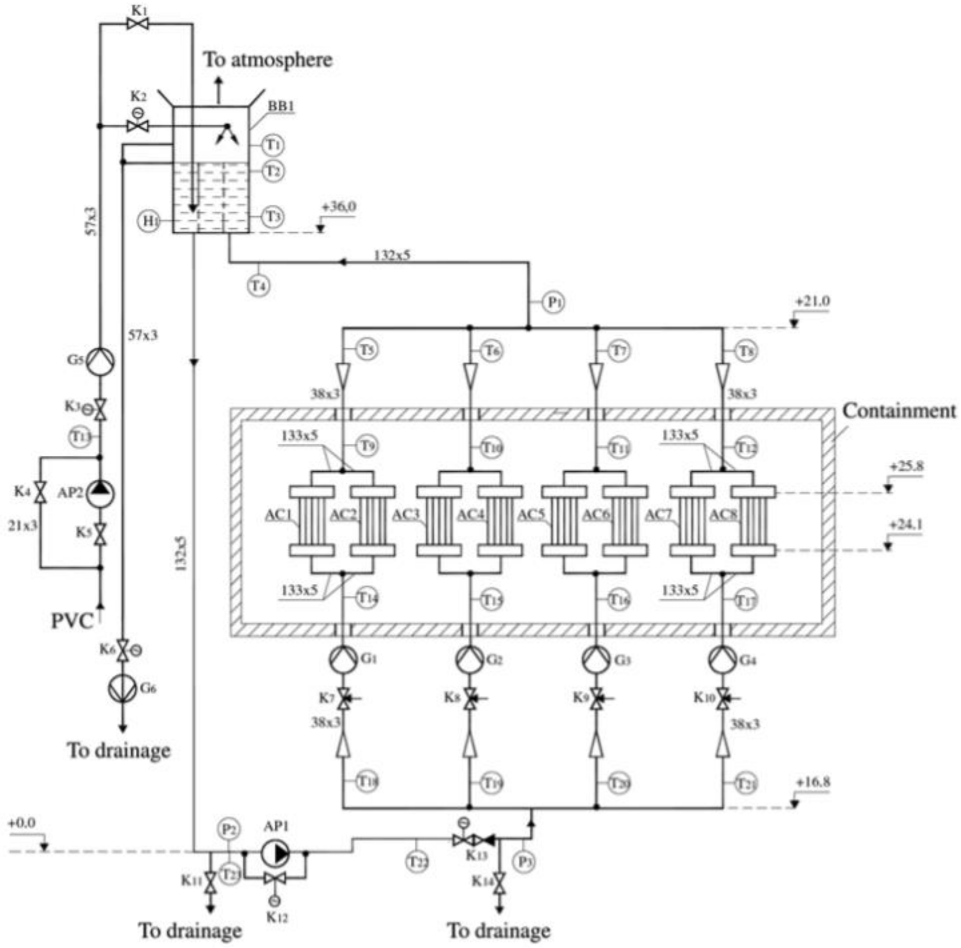

Figure 25: Diagram of KMS system for assessing Containment PHRS performance. (Vasilenko *et al.*, 2014)

6. STEAM GENERATOR PHRS ANALYSIS

Detailed information about steam generator passive heat removal system has been given at section 2.3.1.2. Analysis is based on SG PHRS in V-491, which uses water cooled heat exchangers. In the analysis, SG PHRS will be modeled in both analytically and with thermalhydraulic system code ATHLET.

6.1 Analytical Modeling of SG PHRS

PHRS system utilizes natural circulation in a closed loop. Steam generator is the heat source and heat exchanger is the heat sink. Schematic diagram of the PHRS is shown in Figure 26.

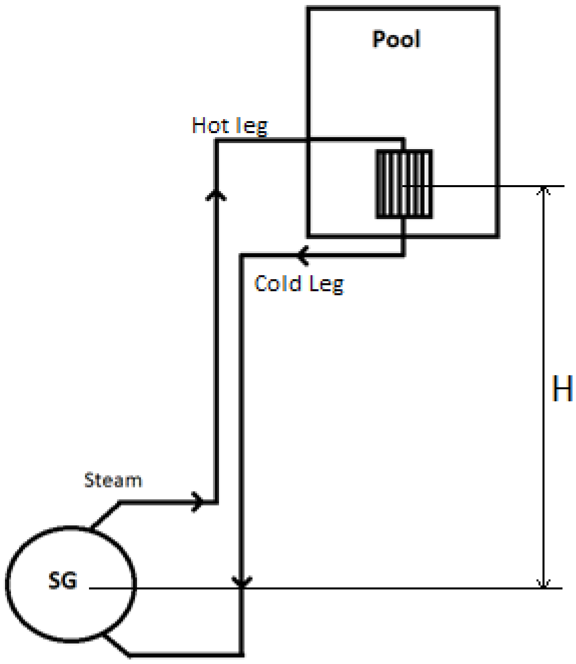

Figure 26: Schematic diagram of SG/PHRS.

Since the SG PHRS stably operates, assumption has been made that steady state conditions were achieved in the loop. Under steady state conditions all time dependent terms are eliminated from momentum equation thus equation (1)can be written as:

$$\Delta p_{gravity} = \Delta p_f \tag{3}$$

Total frictional pressure drop in the circuit is generated from components in loop, such as; steam generator, pipes and heat exchanger in the loop.

$$\Delta \mathrm{p_f} = \Delta p_{f,SG} + \Delta p_{f,pipes} + \Delta p_{f,HE} \quad \textbf{(4)}$$

Frictional and gravitational pressure drop terms in that equation can be written explicitly. System works with two-phase natural circulation, therefore two-phase equations used in analysis.

For the calculation of shell side two-phase pressure drop, Modified Lockhart-Martinelli correlation (Rohsenow *et al.*, 1997) was used.

$$\Delta p_f = \Delta p_{f,l} \Phi_l^2 \quad \textbf{(5)}$$

Where for $Fr_l \leq 0.15$:

$$\Phi_l^2 = 1 + \frac{8}{X_{tt}} + \frac{1}{X_{tt}^2} \quad \textbf{(6)}$$

And

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_v}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_v}\right)^{0.1} \quad \textbf{(7)}$$

Friction pressure loss at pipes can be found by the sum of friction pressure losses inside cold and hot channels. Hot leg covers the pipe section from steam generator outlet to heat exchanger inlet and the cold leg covers the section from heat generator outlet to steam generator inlet (see Figure 26).

$$\Delta p_{f,pipes} = \Delta p_{HL} + \Delta p_{CL} \quad \textbf{(8)}$$

Since both in hot and cold legs two-phase liquid circulate, two-phase friction drop is calculated for each leg. Friction pressure drop including form losses can be found by Darcy-Weisbach correlation.

For hot leg:

$$\Delta \mathrm{p_{HL}} = \frac{\left(\overline{\Phi_{lo}^2}\right)_{HL} \mathrm{q_m^2}}{2\mathrm{A^2}\rho_l} \left(\frac{\mathrm{f_{lo} L_{HL}}}{\mathrm{D_e}} + \sum_{i} \mathrm{K_i}\right) \quad \textbf{(9)}$$

For cold leg:

$$\Delta \mathrm{p_{CL}} = \frac{\left(\overline{\Phi_{lo}^2}\right)_{CL} \mathrm{q_m^2}}{2\mathrm{A^2}\rho_l} \left(\frac{\mathrm{f_{lo} L_{CL}}}{\mathrm{D_e}} + \sum_{i} \mathrm{K_i}\right) \quad \textbf{(10)}$$

Homogenous Equilibrium Model (HEM) was used for pipe sections in order to find two-phase multipliers. In HEM liquid only and vapor only two-phase multiplier are calculated as:

$$\left(\overline{\Phi_{lo}^2}\right) = \frac{\rho_L}{\rho_{TP}} \quad \textbf{(11)}$$

$$\left(\overline{\Phi_{vo}^2}\right) = \frac{\rho_V}{\rho_{TP}} \quad \textbf{(12)}$$

where ρ_{TP} is mixture density. It is calculated from the equation below:

$$\rho_{TP} = \alpha\rho_V + (1-\alpha)\rho_L \quad \textbf{(13)}$$

And the void ratio, α is:

$$\alpha = \frac{1}{\left(1 + \frac{(1-x)}{x}\left(\frac{\rho_V}{\rho_L}\right)S\right)} \quad \textbf{(14)}$$

For HEM slip factor is taken as S=1. In order to find liquid only friction factor f_{lo} for both cold and hot legs Swamee-Jain correlation is used.

$$f = \frac{1.325}{\left[\ln\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \quad \textbf{(15)}$$

Where

$\varepsilon = \frac{k}{D}$ = Friction factor where k is roughness values, which is taken 0.045 mm (steel)

$Re = \frac{GD}{\mu}$ = Reynolds number and $G = \frac{q_m}{A}$

Dynamic viscosity is calculated for two-phase mixture with using equation (16).

$$\mu_{TP} = \left(\frac{x}{\mu_V} + \frac{1-x}{\mu_L}\right)^{-1} \quad \textbf{(16)}$$

To find pressure drop inside the heat exchanger tubes, Friedel correlation used for two-phase multiplier since $\frac{\mu_L}{\mu_V} < 1000$. It is given as (Rohsenow *et al.*, 1997):

$$\Phi_{lo}^2 = E + 3.23\frac{FH}{Fr^{0.045}We^{0.035}} \quad \textbf{(17)}$$

Where

$$E = (1-x)^2 + x^2\frac{\rho_L}{\rho_V}\frac{f_{vo}}{f_{lo}} \quad \textbf{(18)}$$

$$F = x^{0.78}(1-x)^{0.24} \quad \textbf{(19)}$$

$$H = \left(\frac{\rho_L}{\rho_V}\right)^{0.91}\left(\frac{\mu_V}{\mu_L}\right)^{0.19}\left(1 - \frac{\mu_V}{\mu_L}\right)^{0.7} \quad \textbf{(20)}$$

$$Fr = \frac{G^2}{gD_h\rho_{hom}^2} \quad \textbf{(21)}$$

$$We = \frac{G^2 D_h}{\sigma \rho_{hom}} \quad \textbf{(22)}$$

Gravitational pressure change is the term that overcomes the frictional pressure drop in the system. Pressure head is generated by buoyancy(Todreas and Kazimi, 1990).

$$\Delta p_{gravity} = (\rho_h - \rho_c) g H \quad \textbf{(23)}$$

H is the elevation difference between the thermal centers namely Steam Generator and Heat Exchangers as shown in Figure 26.

Therefore, if steam quality is known, mixture density and two-phase multiplier can be calculated from equations (13) and (14). For hot leg steam quality is 1 and for the cold leg it is guessed in the SciLAB script. Mass flow, qm, can also be calculated if steam qualities in hot and cold leg is known.

$$q_m = \frac{Q}{(x_{HL} - x_{CL}) h_{fg}} \quad \textbf{(24)}$$

Q is the heat that will be removed with SG PHRS. Mass flow rate depends on that value since in natural circulation; flow rate is related to heat inserted to the system.

In the SciLAB script after x_C is assigned pressure drops calculated and program checks if gravitational friction drop is equal to frictional pressure drop, if it is not, a new value (+0.01) is assigned for x_C. Iterations continue until the friction pressure drop equals to gravitational pressure head.

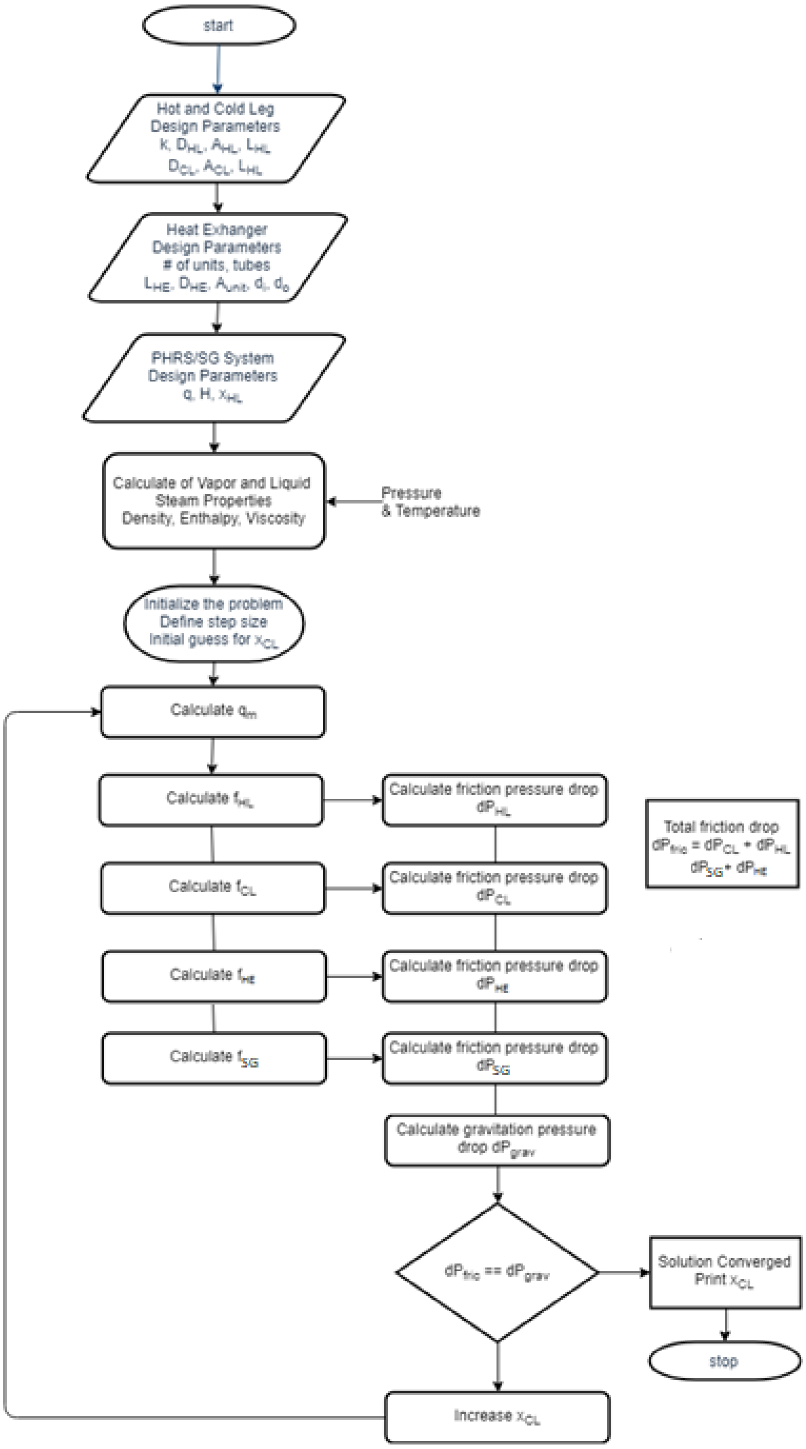

Figure 27: Calculation procedure of the SciLAB script for SG PHRS

6.2 Modeling with ATHLET

6.2.1 ATHLET Code System

ATHLET (Analysis of Thermalhydraulics of Leaks and Transients) is a thermalhydraulic system code from Gesellschaft fur Anlagen- und Reaktorsicherheit (GRS). It is developed for analyzing the nuclear power plant transient, operational conditions and leaks or breaks at the system. ATHLET is suitable for using in design basis and beyond design basis accidents and accident without core damage in light water reactors, such as PWR, BWR, VVER and RBMK.

ATHLET is developed in FORTRAN. Thermalhydraulic analysis depends on basic modules implemented in the code.

- Thermo-Fluiddynamics (TFD)
- Heat Conduction and Heat Transfer (HECU)
- Neutron Kinetics (NEUKIN)
- Control and Balance of Plant (GCSM)

TFD module provides nodular approach in the analysis of the thermalhydraulic system. System can be simulated by different type of fluiddynamic elements(G. Lerchl *et al.*, 2016).

6.2.2 SG PHRS Model

ATHLET model that has been used for the simulation of the SG PHRS is a simplified model of the real system. Model consists of six thermo fluid objects (TFO) and one heat conduction object (HCO). Two separate cycles were used. First cycle is a closed cycle; it starts and ends with steam generator. Second cycle has the PHRS heat exchanger pool and a time dependent boundary, branchout for thermalhydraulic stability of the pool. TFO connections of the model are shown at Figure 28.

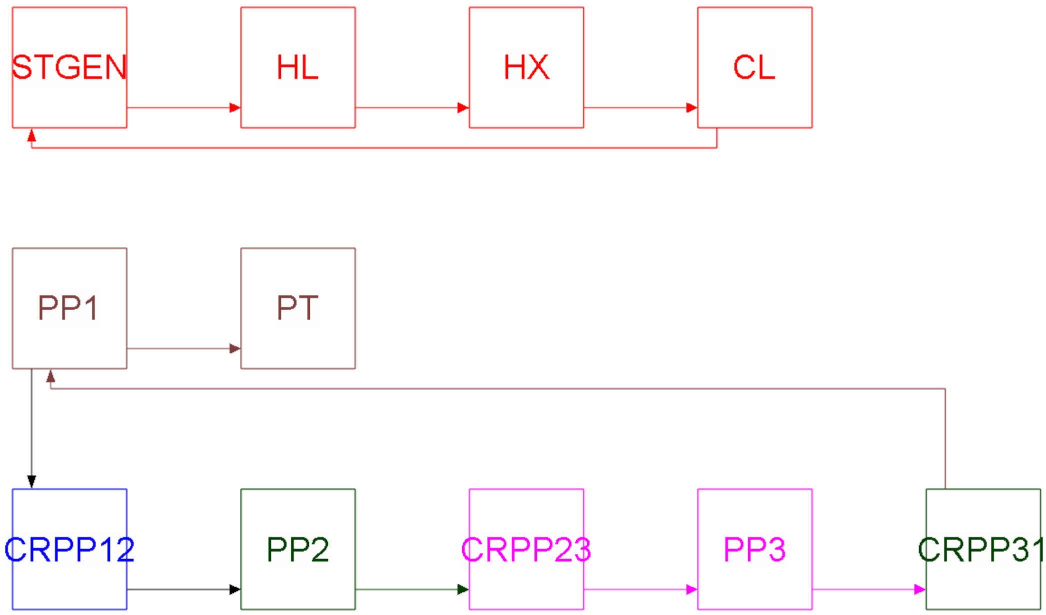

Figure 28: TFO connections in ATHLET model.

In model, STGEN represents the secondary side of the VVER-1200 steam generator. HL and CL represent hot and cold legs of the SG PHRS. HX is the heat exchanger that provides cooling of the circulating fluid and transfer heat to the pool. In order to provide mixing inside the tank, pool is divided in three parts: PP1, PP2 and PP2 CRPPPs are cross connection objects to connect the pool TFOs. PT is the pool top branch, to prevent overpressure inside the pool.

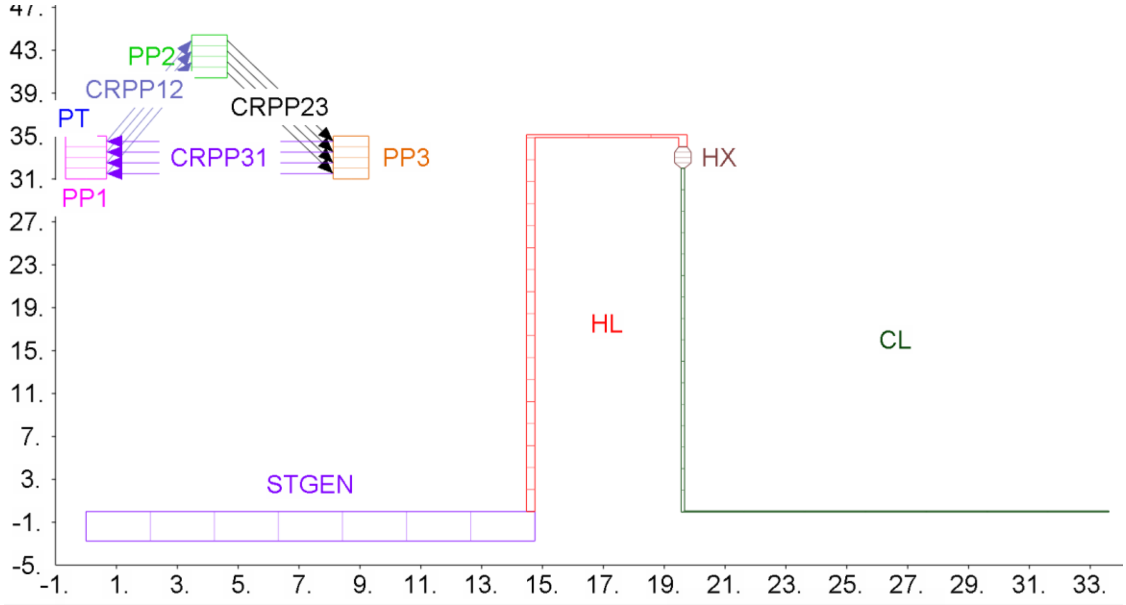

Figure 29: ATHLET model of SG PHRS.

Heat transfer from heat exchanger to the pool is simulated with a heat conduction object. The heat transfer capacity of that HCO is adjusted by using analytical analysis results and real system parameters to construct a proper heat transfer mechanism similar to real system.

ATHLET uses left to right presentation, although system seems open ended in Figure 29, CL returns left after HX exit and enters to STGEN from the left of the STGEN. Therefore, HX is immersed to the pool system represented in left part with PP1, PP2 and PP3 and their connections so that the heat transfer occurs inside the pool.

Elevations and sizing of the components were preserved in the model. Bends were added inside the object as friction losses. Initially first cycle was filled with saturated steam at 70 bar and 285.8 °C and pool temperature was set to 25 °C.

6.3 Results

6.3.1 Analytical Calculation

Thermalhydraulic properties for the analytical model are calculated from steam tables using the steam generator exit steam properties, at 70 bar and 285.8 °C. Dimensions of the system were given at Table 6 lengths and elevation difference were predicted according to drawings of the system.Bends in the legs are 90° degree bends, friction coefficient is taken as 0.45 for 90° bends.

Table 6: PHRS Loop design parameters.

Hot Leg	
Pipe diameter, D [m]	0.273
Total length, L [m]	41
Number of bends	12
Cold Leg	
Pipe diameter, D [m]	0.108
Total length, L [m]	46
Number of bends	14
Elevation difference, H [m]	33
Heat Exchanger	
Number of Units	16
Number of tubes in one unit	140

Length of HE tube [m]	2.12
Inner diameter of tube [m]	0.012

SG PHRS implemented for long term cooling after shutdown of the reactor. When a nuclear reactor shut down, it continues to produce power by the decay of fission products that are generated inside the fuel. For a light water reactor that decay can be seen from decay heat curve given at

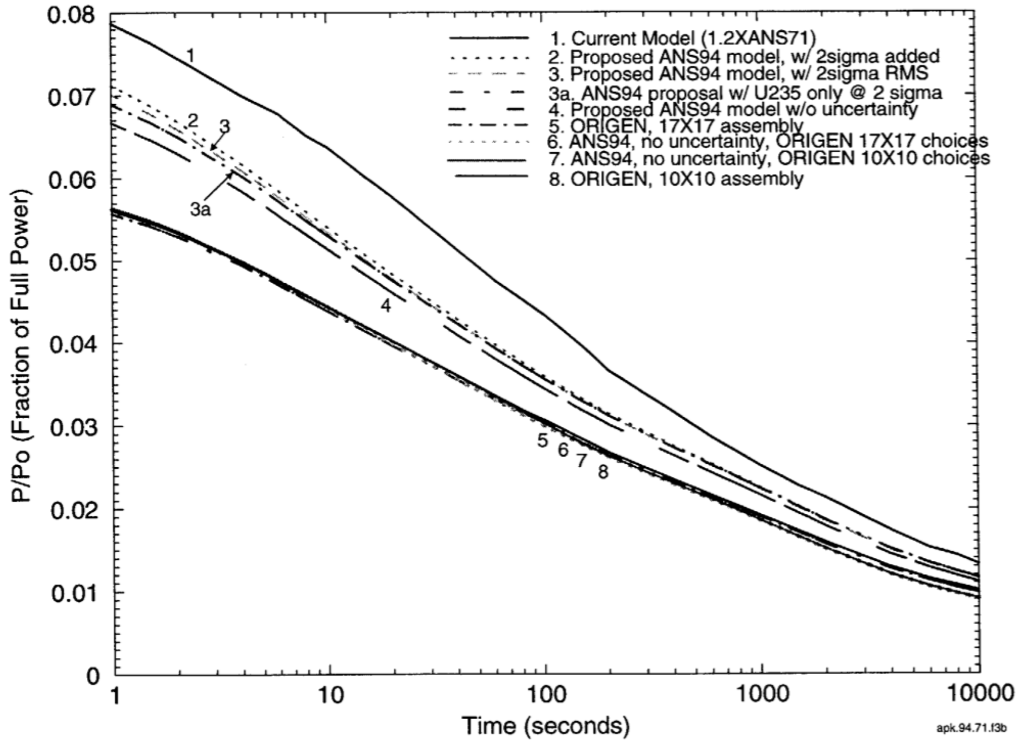

Figure 30: Decay heat curve(NRC, 2004).

SG PHRS activates after 1.5-2 hours from the accident (Morozov and Remizov, 2012). Therefore, system tested for 1% of the nominal power as in Figure 30; since in VVER-1200 nominal thermal power is 3200 MW, system should be able to remove 32 MW core power. Thus in section 2.3.1.2, it has been given that the system could perform its function with diversity of 4x33%. One of the four circuits was considered not to be intact, as a result;32/3=10.67 MW heat removal is necessary for a SG PHRS.

Results of the SciLAB script, phrsSG.sci is given at Table 7. In the SciLAB script after vapor quality at cold leg, x_C is assigned as zero at the start then pressure drops calculated and program checks if gravitational friction drop is equal to frictional pressure drop, if it is not, a new value (+0.01) is assigned for x_C.

Table 7: Analytical calculation results.

Mass flow rate in the loop, q_m [kg/s]	7.705
Cold leg steam vapor quality, x_c	0.08
Friction pressure drop at the loop, Δp_{fric}[kPa]	24.363

6.3.2 ATHLET Simulation

Two decay heat power levels;1 % and 1.5 % of nominal power were considered in simulations. Also number of loops in intact varied from 1 to 4. In total 8 cases were simulated as shown in Table 8.

Table 8: ATHLET simulation cases.

Number of units	Power [MW]		Program Termination	
	1%	1.50%	1%	1.50%
1	32	48	297 secs	211 secs
2	16	24	52.3 hours	385 secs
3	10.67	16	> 83 hours	6.68 hours
4	8	12	> 83 hours	> 83 hours

In the simulation heat added from steam generator as a constant value depending on number of loops in intact and the decay heat ratio. Simulations were run maximum of 300000 secs (83.33 hours). In some cases where power is high simulation stopped because of ATLET FEBE (Forward Euler, Backward Euler) Solver. System was initialized with saturated steam in the loop and subcooled water at the pool. Pool was heated during the simulation depending on the power level pool temperature reaches to boiling temperature after sometime around 2500 secs and stays in boiling temperature thought the simulation (Figure 31).

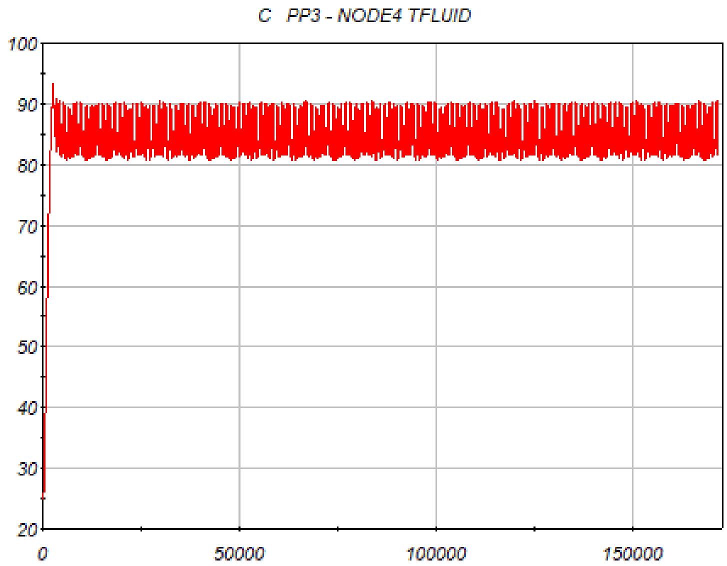

Figure 31: Pool temperature.

Variations in the pool temperature resulted from saturation temperature change with pressure changes inside the pool. System heat transfer mechanism can be seen from Figure 32.

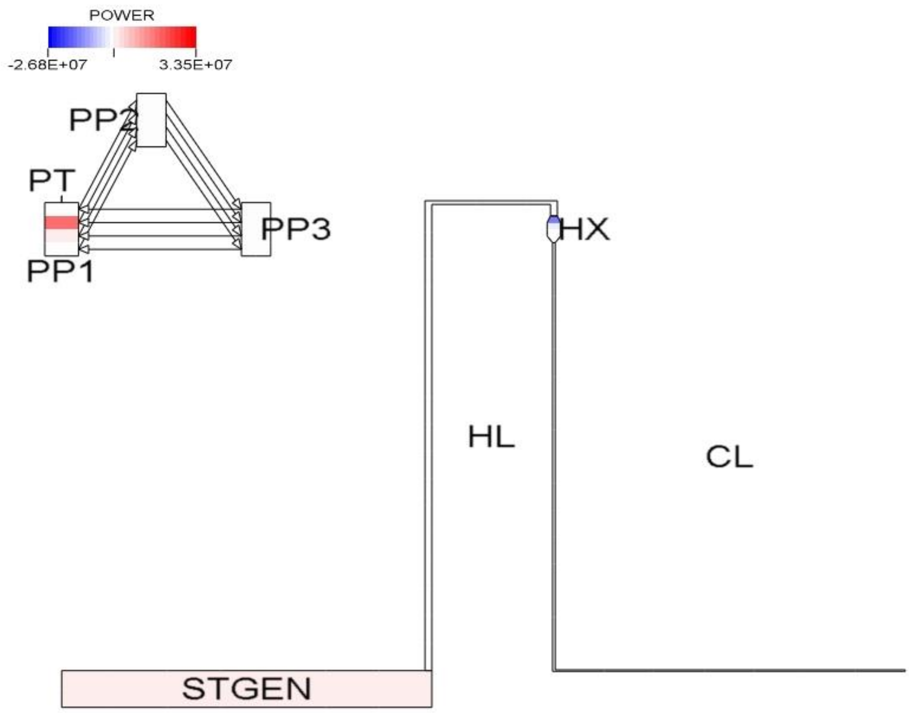

Figure 32: Power distribution for the PHRS ATHLET model.

Mass flows inside the cold leg for 1% decay power and 1.5% decay powers were shown in, Figure 33 and Figure 34. System mass flow was calculated around 2 kg/s.

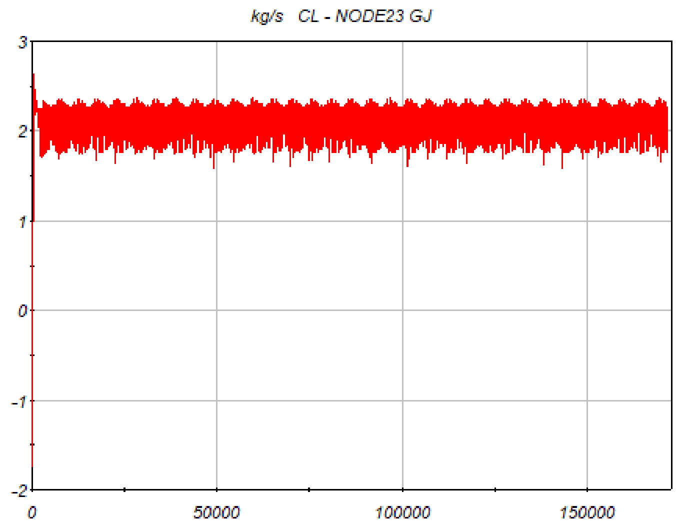

Figure 33: CL mass flow for 1 % Decay heat (3 units).

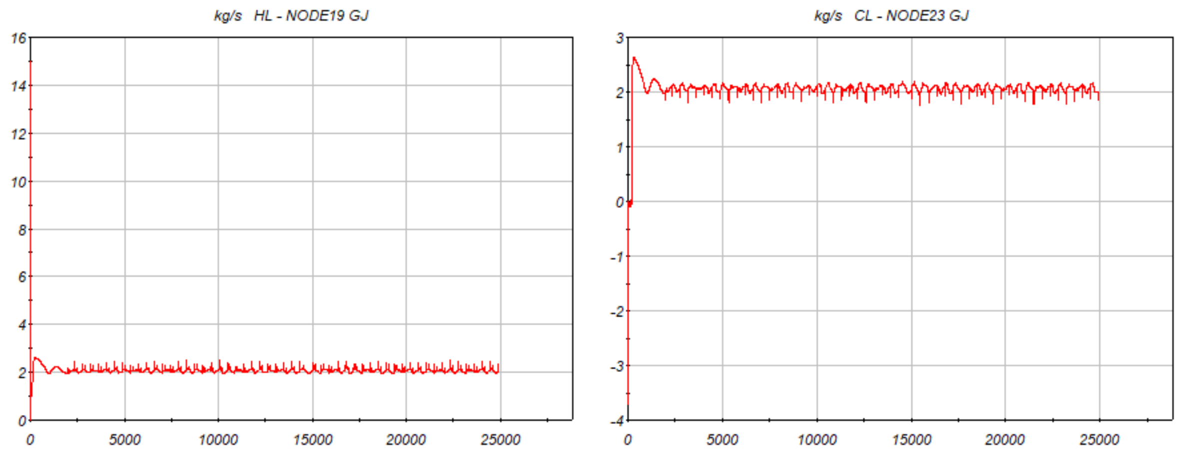

Figure 34: HL and CL mass flows for 1.5 % Decay heat (3 units).

Temperatures at steam generator side and inside the cold leg were shown in Figure 35. It has been seen that for steam generator side the temperature is stable around 280 ^{o}C, and for the cold leg around 90 ^{o}C.

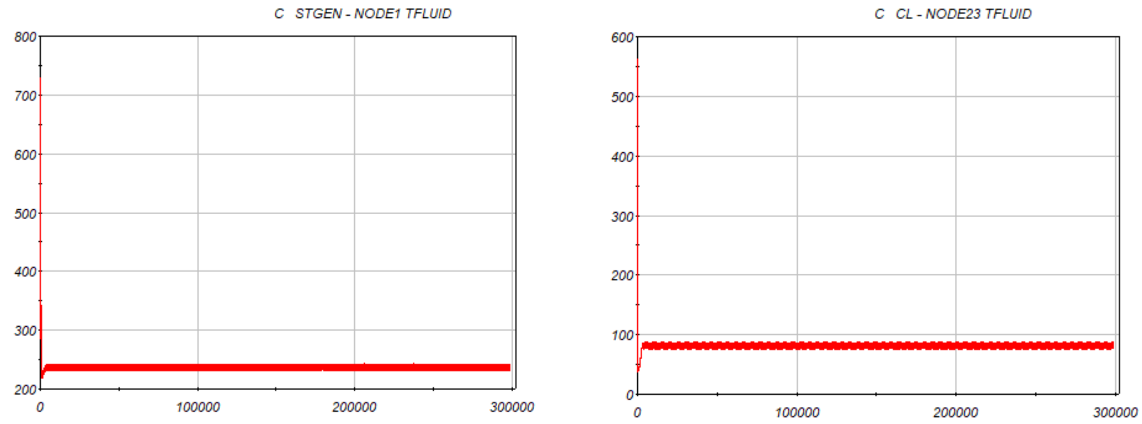

Figure 35: Temperatures at SG and Cold Leg (1 % decay heat).

Void fractions at the inlet of steam generator for 1 % and 1.5 % decay heat ratios were given at Figure 36. It can be seen from graphs that they are both fluctuating around 0.86.

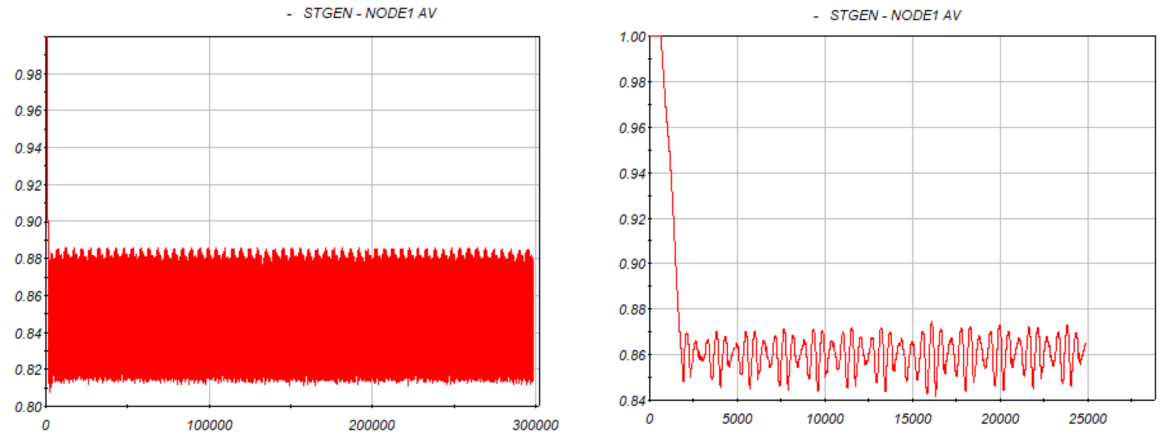

Figure 36: Void fractions at SG inlet for 1 % (left) and 1.5 % decay heats.

Table 9 shows the summary of the ATHLET simulation results in the end of simulation time.

Table 9: Loop parameters from ATHLET simulation.

Mass flow rate in the loop, q_m [kg/s]	2
Pressure in the hot leg, P [MPa]	0.62
Hot leg temperature [°C]	280
Cold leg temperature [°C]	90

7. CONTAINMENT PHRS ANALYSIS

AES-2006 VVER-1200 has also another passive cooling system, which is implemented for cooling of the containment during LOCA. In LOCA large amount of steam exhausted from the break and this steam flow inside the containment. This causes the heating and over-pressurization of the containment. C-PHRS provides heat removal from containment in case of BDBA and protect containment against over-pressurization. Detailed information about steam generator passive heat removal system had been given at section 2.3.1.1. In the analysis, Containment PHRS was modeled analytically.

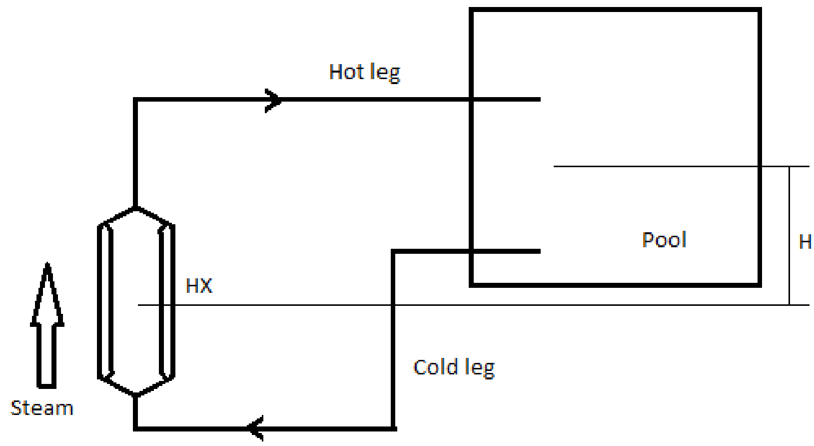

Figure 37: Schematic diagram of Containment PHRS.

One water tank provides water and circulation for two heat exchanger units. The system schematic is shown in Figure 37. The water in the system is heated up from heat exchangers, which receive heat from steam flow inside the containment. After the start of operation, heated water will increase to its boiling point then the circulation will continue as two-phase circulation (driven by quality difference). (Ha, Lee and Kim, 2017)simulated the similar containment cooling system and it can be seen from Figure 38 that water temperature in the tank remains constant at boiling temperature for long term cooling.

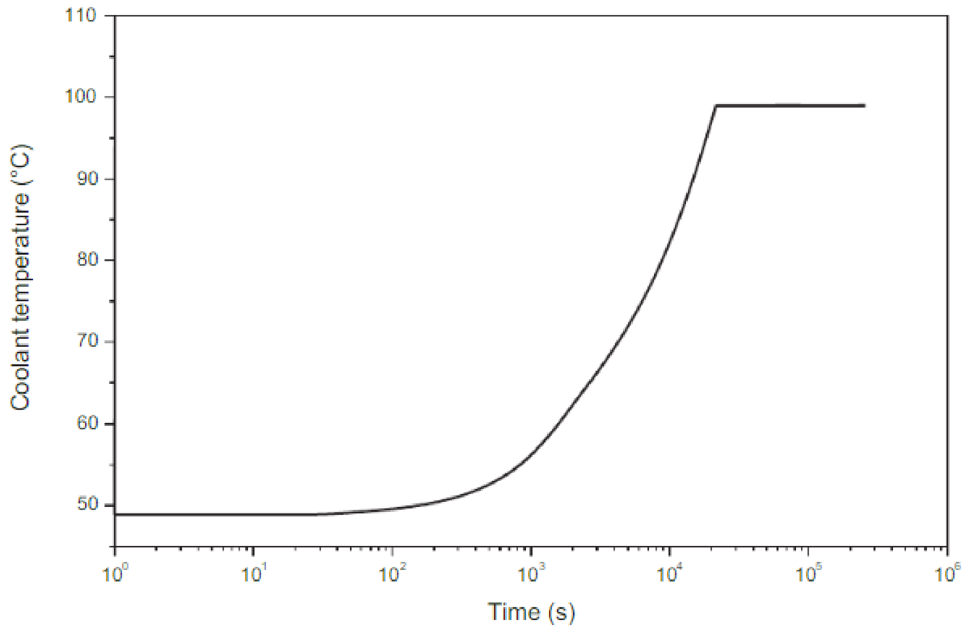

Figure 38: Coolant temperature in a PHRS tank (Ha, Lee and Kim, 2017).

Similar analytical equations that were used for analytical analysis for SG PHRS were used for calculation of pressure drops inside the containment PHRS loop. One unit is modeled in SciLAB code as in shown in Figure 39 with the parameters given at Table 10.

Table 10: Containment PHRS Design Parameters.

Hot Leg	
Pipe diameter, D [m]	0.273
Total length, L [m]	10.5
Number of bends	12
Cold Leg	
Pipe diameter, D [m]	0.108
Total length, L [m]	16.5
Number of bends	14
Elevation difference, H [m]	10.35

For one unit maximum heat input was calculated as 2.496 kW, which increased the exit steam quality to 0.878. Since there are 16 units inside the containment, total heat that can be extracted from containment reaches to 40 kW. This value is possible if the heat exchangers heat transfer capacity is sufficient. Thus, it can also increase if the pressure in the tank increases and if superheat steam conditions is considered. Results for the system working at atmospheric pressure were given at Table 11.

Table 11: Containment PHRS analytical calculation results.

Mass flow rate in one unit, q_m [kg/s]	0.01
Pressure drop in the unit, P [kPa]	8.35
Rejected heat, Q [kW]	2.496
Steam mass quality at cold leg, x	0.879

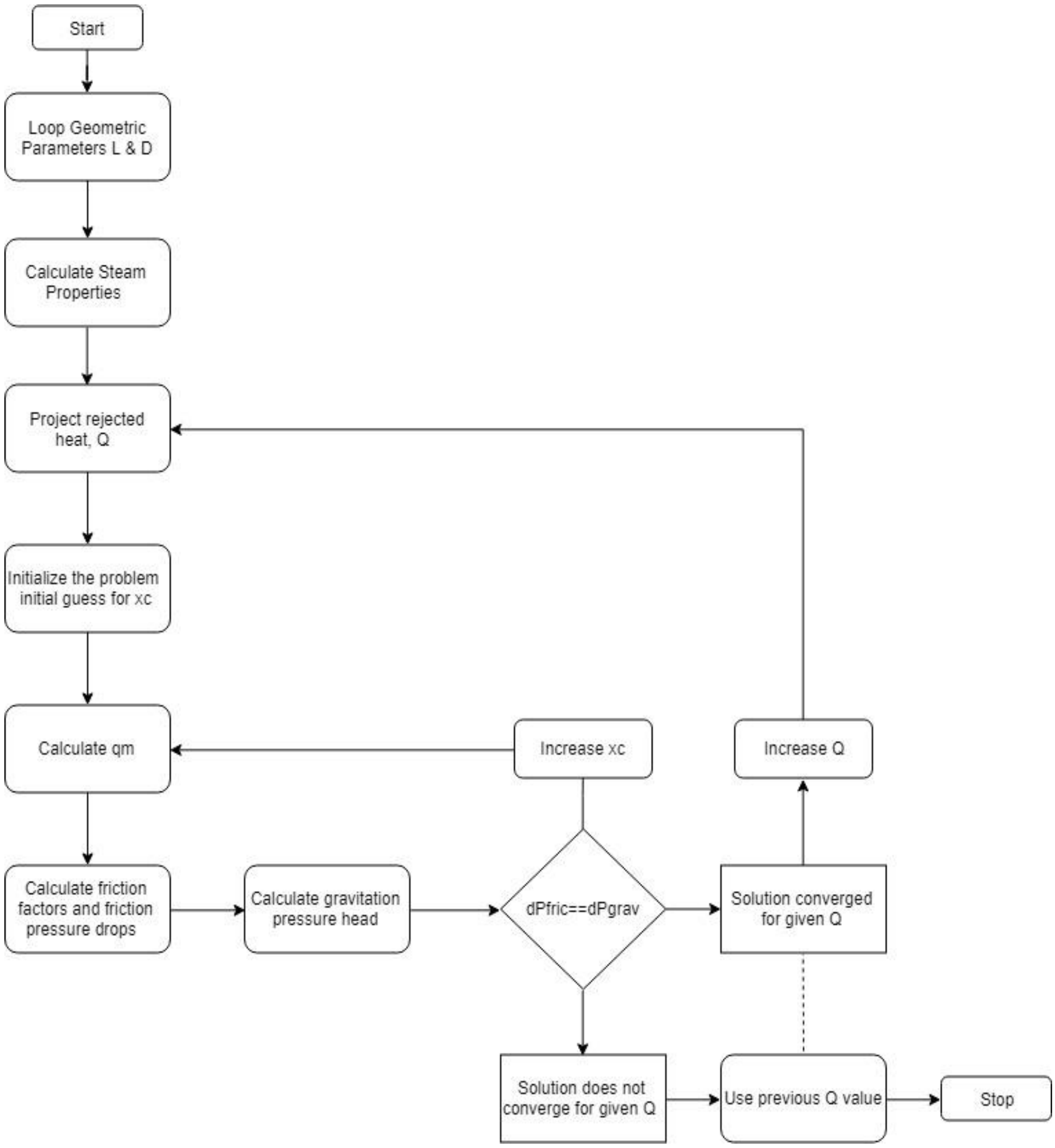

Figure 39: Calculation procedure of the SciLAB script for Containment PHRS.

8. CONCLUSION

Passive systems have been started to be implemented to the new NPP designs of most of the nuclear power plant vendors. Reactors solely rely on passive systems for operation and safety is currently under development.

Natural circulation is an important aspect of a passive safety system. It provides cooling without use of pumps so decreases both equipment and electric consumption costs. Most importantly could operate without need of external power, which can be hard to obtain during severe accident such as Fukushima.

In this thesis general information about natural circulation systems and methods used in the analysis of these systems were given and special attention was given to two new passive safety systems of VVER-1200 AES-2006 NPP.

VVER-1200 includes passive systems for management of the BDBA. Since these systems require no electrical power, they can be relied on in case of total station blackout. To analyze performances of these systems in such conditions, they have been modeled analytically and with system code ATHLET.

The analytical model results used in SG PHRS analysis are shown in section 6.3.1. table 7. We can see that cold leg vapor quality is 0.08 and circulation is established with gravitational friction drop same as frictional pressure drop with that vapor quality value with a low vapor quality value. Thus, system performs its function for the given boundary condition.

The analytical model used in SG PHRS analysis approved that the system could perform its function for a given boundary condition. Since it is a steady state calculation, it can be concluded that, if the system parameters remain as it is, cooling can prolong for a long time. However, the heat transfer mechanism is not included in analytical solution so that, it is expected that the conditions will vary in normal operation.

SG PHRS model was constructed in order to see the system behavior for removal of decay heat for prolonged situation. Eight cases were modeled in ATHLET simulations in chapter

6. Results of these simulations are shown in section 6.3.2. As can been seen from table 8, PHRS can steadily remove 1% and 1.5 % ratio decay heats for given simulation time (83.33 hours). In the case of failure in the one of the four legs, again system can perform successfully as long as the simulation time for 1 % decay heat. In section 2.3.1.2, it has been reported that the PHRS design can cool down the reactor for 72 hours with one leg failure. At table 8, we can also see the simulation case for one failed leg with 1.5 % decay heat. Failure time for that case is calculated as 6.68 hours. This result seems to contradict the claimed design performance of 72 hours, but in the simulation heat assumed as constant, which in realty it reduces with time as shown in figure 30: decay heat curve, and from the same figure it takes around 1 hour (3600 seconds) for decay power fraction to drop from 0.015 to 0.01. Therefore, for better analysis change in decay heat ratio with time should also be included in simulation.. Previous work at LUT for analyzing the natural circulation in passive heat removal system via steam generators also showed that the three loops have enough capacity to provide safety in reaching necessary safety levels (Dmitrii, 2016).

Another analytical model was constructed for passive heat removal system containment cooling. The difference is that this system cools the steam inside the containment. Therefore, instead of steam extracted from secondary side of steam generators in SG PHRS, cooling water circulates inside the containment PHRS. Thus, a different methodology was followed; since the heat that considered to be removed is not known, maximum possible heat removal was calculated in the analytical model.

Therefore, it can be said that basic analytical analysis gives a valuable insight for the analysis with system code. Stability of the system can be observed with the analytical analysis. Thus, it can be used for basic preliminary design of a natural circulation system.

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APPENDIX 1: Scilab scripts

<u>phrsSG.sci</u>

```
//PASSIVE RESIDUAL HEAT REMOVAL SYSTEM
//STEAM GENERATOR
//Single SG

clc
clearall

//Using Xsteam for steam properites
exec("XSteam_main.sci",-1)
// T     Temperature (deg C)
// p                    Pressure    (bar)
// h                    Enthalpy    (kJ/kg)
// v                    Specific volume (m3/kg)

//Loop design parameters
//Rougness
k=0.045//Steel

D_h=273e-3
A_h=(%pi*D_h^2)/4
L_h=41//aprox

D_c=108e-3
A_c=(%pi*D_c^2)/4
L_c=46//aprox

//SG Desing parameters
D_SG=4.0
d_SG_tube=19.05e-3
L_SG=13.85
A_SG=(%pi*D_SG^2)/4
P_SG=D_SG*%pi

//HE Design parameters
num_u=16//number of units
num_t=140//number of tubes in one unit
L_HEtube=1.95
L_HE=2.124
D_HEtube=0.08
di_tube=0.012
do_tube=0.016
A_tube=(%pi*di_tube^2)/4

//System design parameters
q=10.67e3//kW heat to be rejected at HE and SG
H=33//difference between SG and HE (approx)
xh=1.//saturated steam same in hot leg

//Thermalhyraulics in the loop
P=70//bar
T=285.8//C
rhoV=XSteam("rhoV_p",P)
rhoL=XSteam("rhoL_p",P)
hV=XSteam("hV_p",P)
hL=XSteam("hL_p",P)
hfg=hV-hL
myV=XSteam("my_ph",P,hV)
myL=XSteam("my_ph",P,hL)

//MOMENTUM BALANCE
//Gravity dp should be equal to friction dp
margin=0.01//%1
xc=0.05//intial guess for HE exit samen in cold leg
```

```
step_size=0.001//for xc
step_number=0
dp_f=1
dp_g=2
xfinal=0

whileabs(dp_f-dp_g)>margin*max([dp_f,dp_g])do//Control section

qm=q/((xh-xc)*hfg)


//Calculation of 2p parameters
// HEM model
S=1

//Loop parameters
//Hot leg
G_h=qm/A_h
v_h=G_h*rhoV
Re_h=G_h*D_h/myV
eps_h=k/(D_h*1000)
f_h=1.325*(log((eps_h/D_h)/3.7+5.74/Re_h^0.9))^-2//Swamee-Jain

//Cold leg
alpha_c=1/(1+((1-xc)/xc)*(rhoV/rhoL)*S)
rho_c=alpha_c*rhoV+(1-alpha_c)*rhoL
my_c=(xc/myV+(1-xc)/myL)^-1//McAdams
phi2_lo_c=rhoL/rho_c
G_c=qm/A_c
Re_c=G_c*D_c/my_c
eps_c=k/(D_c*1000)
f_c=1.325*(log((eps_c/D_c)/3.7+5.74/Re_c^0.9))^-2//Swamee-Jain

//PRESSURE DROPS
Kbend=0.45//90 degree
//Hot leg
bends_h=12//90 degree(aprox) until flow separation inside pool
Kvalve_h=Kbend*bends_h
dp_h=qm^2*(f_h*L_h/D_h+Kvalve_h)/(2*A_h^2*rhoV)

//Steam Generator
xSG=(xh+xc)/2
rho_SG=xSG/rhoV+(1-xSG)/rhoL
G_SG=qm/A_SG

my_SG=(xSG/myV+(1-xc)/myL)^-1//McAdams
//Modified Lockhart-Matinello Correlation
D_h_SG=4*%pi*A_SG/P_SG
//    Fr_HE=G_SG^2/(9.8*D_h_SG*rho_SG^2)
Xtt=((1-xSG)/xSG)^.9*(rhoV/rhoL)^.5*(myL/myV)^.1
phi2_l_SG=1+8/Xtt+1/Xtt^2
Re_l_SG=G_SG*(1-xSG)*D_h_SG/myL
f_l_SG=0.079/Re_l_SG^0.25
dp_l_SG=f_l_SG*(2*L_SG/D_h_SG)*G_SG^2/(9.8*rhoL)
dp_SG=phi2_l_SG*dp_l_SG

//Cold leg
bends_c=14//90 degree(aprox) from flow combination to SG
Kvalve_c=Kbend*bends_c
dp_c=phi2_lo_c*qm^2*(f_c*L_c/D_c+Kvalve_c)/(2*A_c^2*rhoL)

//Heat Exchanger
qm_HE=qm/(num_u*num_t)
//    rho_HE=(rho_h+rho_c)/2
xHE=(xh+xc)/2
rhoHE=xHE/rhoV+(1-xHE)/rhoL
my_HE=(xHE/myV+(1-xc)/myL)^-1//McAdams
//    phi2_lo_HE=rhoL/rho_HE
```

```
G_HE=qm_HE/A_tube
//    v_HE=G_c*rho_HE
D_h_HE=di_tube
//    Re_HE=rho_HE*v_HE*v_HE/my_HE
Re_HE_lo=G_HE*D_h_HE/myL
Re_HE_vo=G_HE*D_h_HE/myV

eps_HE=k/(di_tube*1000)
f_HE_lo=1.325*(log((eps_c/di_tube)/3.7+5.74/Re_HE_lo^0.9))^-2//Swamee-Jain
f_HE_vo=1.325*(log((eps_c/di_tube)/3.7+5.74/Re_HE_vo^0.9))^-2

//Friedel correlation
E=(1-xHE)^2+xHE^2*(rhoL/rhoV)*(f_HE_lo/f_HE_vo)
F=xHE^0.78+(1-xHE)^0.24
H=(rhoL/rhoV)^0.91*(myV/myL)^0.19*(1-myV/myL)^0.7
Fr_HE=G_HE^2/(9.8*D_h_HE*rhoHE^2)
sigmaHE=0.0588//Surface tension of water @100C
We_HE=G_HE^2*D_h_HE/(sigmaHE*rhoHE)

phi2_lo_HE=E+3.238*F*H/(Fr_HE^0.045*We_HE^0.035)


KbendHE=0.25//45 degree
bends_HE=4
Kvalve_HE=KbendHE*bends_HE
dp_HE=phi2_lo_HE*qm_HE^2*(f_HE_lo*L_HE/di_tube+Kvalve_HE)/(2*A_tube^2*rhoL)


//Total friction loss
dp_f=dp_h+dp_c+dp_HE+dp_SG

//Gravity
g=9.8
dp_g=(rho_c-rhoV)*g*H

mprintf('at iteration %i, xc=%f \n,Gc=%f \n',step_number,xc,G_c)
xfinal=xc
step_number=step_number+1
xc=0.05+step_size*step_number
end

mprintf('Problem converged for xc=%f',xfinal)
```

phrsCO.sci

```
//PASSIVE RESIDUAL HEAT REMOVAL SYSTEM
//INNER CONTAINMENT

clc
clearall

//Using Xsteam for steam properites
exec("XSteam_main.sci",-1)
// T     Temperature (deg C)
// p                 Pressure    (bar)
// h                 Enthalpy    (kJ/kg)
// v                 Specific volume (m3/kg)

//Loop design parameters
//Rougness
k=0.045//Steel

L_h=10.5
D_h=273e-3
A_h=(%pi*D_h^2)/4

L_c=16.5
```

```
D_c=108e-3
A_c=(%pi*D_c^2)/4

//System design parameters
q=2.496//kW heat to be rejected at HE and SG
H=10.35//difference between SG and HE (approx)
xh=1.//saturated steam same in hot leg

//Thermalhyraulics in the loop
P=1//bar
T=100//C
rhoV=XSteam("rhoV_p",P)
rhoL=XSteam("rhoL_p",P)
hV=XSteam("hV_p",P)
hL=XSteam("hL_p",P)
hfg=hV-hL
myV=XSteam("my_ph",P,hV)
myL=XSteam("my_ph",P,hL)

//MOMENTUM BALANCE
//Gravity dp should be equal to friction dp
margin=0.01//%1
xc=0.05//intial guess for HE exit samen in cold leg
step_size=0.001//for xc
step_number=0
dp_f=1
dp_g=2
xfinal=0

whileabs(dp_f-dp_g)>margin*max([dp_f,dp_g])do//Control section

qm=q/((xh-xc)*hfg)

//Calculation of 2p parameters
// HEM model
S=1

//Loop parameters
//Hot leg
alpha_h=1/(1+((1-xh)/xh)*(rhoV/rhoL)*S)
rho_h=alpha_h*rhoV+(1-alpha_h)*rhoL
my_h=(xh/myV+(1-xh)/myL)^-1//McAdams
phi2_lo_h=rhoL/rho_h
G_h=qm/A_h
v_h=G_h*rho_h
Re_h=G_h*D_h/my_h
eps_h=k/(D_h*1000)
f_h=1.325*(log((eps_h/D_h)/3.7+5.74/Re_h^0.9))^-2//Swamee-Jain

//Heat Exchanger



//Cold leg
alpha_c=1/(1+((1-xc)/xc)*(rhoV/rhoL)*S)
rho_c=alpha_c*rhoV+(1-alpha_c)*rhoL
my_c=(xc/myV+(1-xc)/myL)^-1//McAdams
phi2_lo_c=rhoL/rho_c
G_c=qm/A_c
v_c=G_c*rho_c
Re_c=rho_c*v_c*v_c/my_c
eps_c=k/(D_c*1000)
f_c=1.325*(log((eps_c/D_c)/3.7+5.74/Re_c^0.9))^-2//Swamee-Jain

//PRESSURE DROPS
Kbend=0.45//90 degree
//Hot leg
bends_h=12//90 degree(aprox) until flow separation inside pool
```

```
Kvalve_h=Kbend*bends_h
dp_h=phi2_lo_h*qm^2*(f_h*L_h/D_h+Kvalve_h)/(2*A_h^2*rhoL)

//Cold leg
bends_c=14//90 degree(aprox) from flow combination to SG
Kvalve_c=Kbend*bends_c
dp_c=phi2_lo_c*qm^2*(f_c*L_c/D_c+Kvalve_c)/(2*A_c^2*rhoL)

//Heat Exchanger

//Total friction loss
dp_f=dp_h+dp_c

//Gravity
g=9.8
dp_g=(rho_c-rho_h)*g*H

mprintf('at iteration %i, xc=%f \n',step_number,xc)
xfinal=xc
step_number=step_number+1
xc=0.05+step_size*step_number
end

mprintf('Problem converged for xc=%f',xfinal)
```

APPENDIX 2: Athlet Code

```
PRINT ON
HTML ON
@++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@    CONTROL WORD  ************
C---- HEADER

   ATHLET 3.1A
                ================================================================
                SG PHRS Natural Circulation Modeling
  ================================================================

@++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@    CONTROL WORD  ************
C---- PARAMETERS
@   Parameters for System 1:
   PINLET = 70.D5       TINLET = 285.8
@
@
@++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@    CONTROL WORD  ************
C---- CONTROL
@
@    DTPRIN  ISPRIN INPPRN IPLPRN IGPPRN DTPLOT ISPLOT SGPLOT    ITPLOT
     2.0D+01 10000  4      1      1      1.0    200000 'DEFAULT' 0
@
@    MZEIT MCPU ICPUTM MIZS TE   SGEND
     5    0    1      0  2400.0 'DEFAULT'
@
@    IWBER IPUNC ISREST
     0    2    0
@
@    TPNTWR(I)
     20.      40.      60.
@++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@    CONTROL WORD ***********
C---- TOPOLOGY
@    1ST PRIORITY CHAIN
----- SGSIDE
@
@    IPRI0 ISYS0
     1    1
@   SBO0     ANAMO    SEO0  IARTO
0.000    STGEN   14.75     1
                0.000    HL      41.0      1
   0.000    HX       2.1      1
   0.000    CL      46.0      1
                0.000    STGEN    4.2      1

@    2ST PRIORITY CHAIN
----- POOLSIDE
@
@    IPRI0 ISYS0
1     2
@   SBO0     ANAMO    SEO0  IARTO
                0.000            POOL      4.0      1
0.000    BRACHOUT  0.0      1

@    CONTROL WORD ************
C---- OBJECT
@
K---- STGEN
@    ITYPO FPARO ICMPO
     21    1.0   0
----- NETWORK
@    SN0(I) NI0(I)
0.0    25
```

```
14.75
@
----- GEOMETRY
@     SG0    Z0                     D0               A0     V0     DEP0
    0.0    0.0    2.75    0.0    0.0    0.0
   14.75    0.0   2.75    0.0    0.0    0.0

----- INITCOND
@     SI0    P0       T0       G0                   Q0   ICK00
     0.000  70.D5     285.8     0.0   7.339D5  3
@

K---- HL
@     ITYPO FPARO ICMPO
21    1.0   0
----- NETWORK
@     SN0(I) NI0(I)
     0.0    41
     41.00
@
@----- JUNTYPES
@  ST0       JTYP0     ATYP0
@   0.0       6         'FINLET'
@
----- GEOMETRY
@     SG0    Z0                     D0               A0     V0     DEP0
    0.0    0.0    0.273    0.0    0.0    0.0
                 35.0   35.0    0.273    0.0    0.0    0.0
                 40.0   35.0    0.273    0.0    0.0    0.0
                 41.0   34.0    0.273    0.0    0.0    0.0
@
----- FRICTION
@    ITPMO      ALAMO      ROUO
     2          0.0          0.045
@     SF0        SDFJ0      ZFFJ0      ZFBJ0
                 0.5          0.0        131.335        131.335
                  1.0          0.0        131.335        131.335
                  1.5          0.0        131.335        131.335
                  2.5          0.0        131.335        131.335
                  6.0          0.0        131.335        131.335
                  9.0          0.0        131.335        131.335
                 20.0          0.0        131.335        131.335
                 21.0          0.0        131.335        131.335
                 22.0          0.0        131.335        131.335
                 24.0          0.0        131.335        131.335
                 25.0          0.0        131.335        131.335
                 28.0          0.0        131.335        131.335
                 30.0          0.0        131.335        131.335
                 32.0          0.0        131.335        131.335
                 35.0          0.0        131.335        131.335 @ 90 bend
                 36.0          0.0        525.342        525.342
                 40.0          0.0        525.342        525.342 @ 90 bend w half size pipe
@
----- INITCOND
@     SI0    P0       T0       G0                   Q0   ICK00
     0.000  70.D5     285.8     0.0    0.0  3
@

K---- HX
@     ITYPO FPARO ICMPO
21    2240.0   0
----- NETWORK
@     SN0(I) NI0(I)
0.0    21
2.1
@
----- GEOMETRY
@     SG0    Z0                     D0               A0     V0     DEP0
```

```
     0.0    34.0    0.012  0.0    0.0    0.0
                    2.1    32.0    0.012  0.0    0.0    0.0
@
----- FRICTION
@    ITPMO      ALAMO      ROUO
     1         0.0694      0.045
@     SF0        SDFJ0      ZFFJ0      ZFBJ0
                     0.35       0.0    35180967.    35180967.
                     1.75       0.0    35180967.    35180967. @ 45 bend
@
----- INITCOND
@     SI0    P0        T0        G0                    Q0   ICK00
     0.000  70.D5     285.8      0.0     0.0  3
@
@
K---- CL
@     ITYPO FPARO ICMPO
21    1.0   0
----- NETWORK
@     SN0(I) NI0(I)
0.0    46
46.00
@
----- GEOMETRY
@     SG0    Z0                    D0               A0     V0     DEP0
    0.0   32.0    0.108    0.0    0.0    0.0
                  32.0    0.0    0.108    0.0    0.0    0.0
                  46.0    0.0    0.108    0.0    0.0    0.0
@
----- FRICTION
@    ITPMO      ALAMO      ROUO
     1         0.0281        0.0
@     SF0        SDFJ0      ZFFJ0      ZFBJ0
                  0.2         0.0      5362.     5362.
                     1.5         0.0      5362.     5362.
                     2.0         0.0      5362.     5362.
                     4.0         0.0      5362.     5362.
                     5.2         0.0      5362.     5362.
                     7.0         0.0      5362.     5362.
                     9.0         0.0      5362.     5362.
                    20.0         0.0      5362.     5362.
                    22.2         0.0      5362.     5362.
                    35.0         0.0      5362.     5362.
                    36.0         0.0      5362.     5362.
                    37.0         0.0      5362.     5362.
                    37.5         0.0      5362.     5362.
                    38.0         0.0      5362.     5362.
                    42.0         0.0      5362.     5362. @ 90
                    44.0         0.0     21448.    21448. @ 90 w half size
@
----- INITCOND
@     SI0    P0        T0        G0                    Q0   ICK00
0.000  70.D5     285.8      0.0     0.0  3
@

@POOL SIDE-----------------------------------

K---- POOL
@     ITYPO FPARO ICMPO
     21    1.0   0
----- NETWORK
@     SN0(I) NI0(I)
     0.0    16
     4.0
@
----- GEOMETRY
@     SG0    Z0                    D0               A0     V0     DEP0
0.0    31.0   12.0    0.0    0.0    0.0
```

```
                    4.0    35.0   12.0    0.0    0.0    0.0
@
----- INITCOND
@     SI0    P0        T0    G0                    Q0   ICK00
     0.000  1.D5     25.0   0.0  0.0  1

K---- BRACHOUT
@     ITYPO FPARO ICMPO
     1     1.0   5
----- GEOMETRY
@     SG0    Z0                    D0              A0     V0     DEP0
     0.0    35.0    0.4    0.0    0.0    0.0
     0.5    35.5    0.4    0.0    0.0    0.0
----- INITCOND
@     SI0    P0        T0    G0                    Q0   ICK00
0.000  0.0      25.0   0.0  0.0  1

@+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@     CONTROL WORD ***********
C---- TIMEDEPVOL
@
K---- BRACHOUT
@   SGPRES      SGENTH
   'TDV02P'     'TDV02H'
@
@+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@     CONTROL WORD ***********
C*--- FILL
@
@+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@     CONTROL WORD ***********
C*--- VALVE
@
@+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@     CONTROL WORD ***********
C---- INTEGRAT
@
@     H0       T        EPS      ECKSCH   GRESCH
     1.0D-02  0.0D+00  1.0D-03  1.0D-06  2.0D-08
@
@     HMAX    SGHMAX    DTAV    IFTRIX IGFTRX ISFTRX I2MFTRX ITYPTS IOTS
     1.0D+00 'DEFAULT' 0.0D+00 0      0      0      0       1      0
@
@     T11(1...6)
     0.0D+00   0.0D+000.0D+000.0D+000.0D+000.0D+00
@
@     TOEXP    TOIMP    TOFTX    TOEIG    TOFKT    TOJAC
     1.0D+06  1.0D+061.0D+061.0D+06  0.0D+00  1.0D+06
@+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@     CONTROL WORD ***********
C---- MISCELLAN
@
@
K---- DRUFAN
@
@     AA       BB       CC       DD       EE
1.0D+10  0.0D+00  0.0D+000.0D+000.0D+00
@
@     FF       GG       OO       PP       QQ
&     0.0D+00  0.1D+00  0.0D+00  0.0D+000.0D+00
@
@
@+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@     CONTROL WORD ***********
C---- HEATCOND
@
@  IHV  IOPTHC
    1     3
```

```
@
@ HECONV   TFCONV
  1.D-2   1.D-2
@
@ IPOL      IHTC    IQAXH
    1      1      0
@
 PWALL
@
K---- PWALL
@ AOLH        SBOLH  SEOLH   AORH        SBORH  SEORH
  'HX'        0.0    2.1    'POOL'       3.0    0.9
@
@  NIHC0 N10 N20 N30 IGEO0 ICOMP0 ACOMP0    ICHF0 IPRIPLO
   1     10  0   0   2     0      'DUMMY'     2     0
@
----- GEOMETRY
@ FPARH    TL0
  2112.0    0.0
@
COPY_TFO L
@ SG0    Z0     DI0     DS10     GAP10     DS20      GAP20    DS30
  0.00   34.0   0.004   0.004     0.0       0.0       0.0      0.0
@
----- HTCDEF
@ AIAL(1...4)
 'HTCCALC'  'HTCCALC'  'DUMMY'  'DUMMY'
@
@ SH0      HTCL0(1...4)                         QTHRU0
  0.       4.D4     4.D4   0.0      0.0            0.0
@
----- MATPROP
@  AMATL(1...3)
 'FERR-STEEL'    'DUMMY'   'DUMMY'
@
@------------------------------------------------------------------------
@++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@    CONTROL WORD ***********
C*--- ROD
@
@++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@    CONTROL WORD ***********
C---- GCSM
@
@  >>>>PROCESS SIGNALS<<<<
@
S---- PROBLEM TIME
@    YNAME      VARTYP     OBJNAM     MODNAM     SPV0
     PROB.TIME   TIME       -          -          0.
@
@  >>>>CONTROL SIGNALS<<<<
@
----- CBLOCK1
@    1. CONTROL BLOCK
@
@    IPRI  ICB  INTEK  DTMAX
     0    2    1      1.0000E+00
@
@  TDV signals ***************************************
@
S---- BRACHOUT PRESSURE SIGNAL
@ YNAME    CONTYP    X1NAME    X2NAME    X3NAME    X4NAME
  TDV02P   ADDER     -         -         -         -
@ IOPT     GAIN      A1        A2        A3        A4
  0        1.        1.0D5     0.        0.        0.
@
S---- BRACHOUT TEMPERATURE SIGNAL
@ YNAME    CONTYP    X1NAME    X2NAME    X3NAME    X4NAME
```

```
 TDV02T   ADDER    -      -      -      -
@ IOPT    GAIN     A1      A2      A3      A4
 0       1.       25.     0.      0.      0.
@
S---- BRACHOUT SPECIFIC ENTHALPY SIGNAL
@ YNAME    CONTYP    X1NAME    X2NAME    X3NAME    X4NAME
 TDV02H   PROP      TDV02P    TDV02T    -      -
@ IOPT    GAIN     A1      A2      A3      A4
 4       1.      -1.      1.      0.      0.
@
@+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@     CONTROL WORD ***********
C---- TABLES
@
@+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
@END OF DATASET
```